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Soil Moisture Workshop

A conference held at the
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Beltsville, Maryland
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Soil Moisture Workshop

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PREFACE

The Soil Moisture Workshop was jointly sponsored by the National Aeronautics and Space Administration, Goddard Space Flight Center (NASA/GSFC) and the United States Department of Agriculture Science and Education Administration (USDA-SEA). The joint sponsorship of the Workshop by NASA and the USDA emphasized the widespread interest in soil moisture which served as the catalyst to encourage participation of those individuals involved with the various facets of soil moisture measurement and application. The keynote addresses by Carl Carlson of the USDA and Leslie Meredith of GSFC depicted the USDA's needs for soil moisture information and NASA's role in addressing those needs.

The Soil Moisture Workshop was held at the United States Department of Agriculture National Agricultural Library in Beltsville, Maryland on January 17-19, 1978. The objectives of the Workshop were to evaluate the state of the art of remote sensing of soil moisture; examine the needs of potential users; and make recommendations concerning the future of soil moisture research and development. To accomplish these objectives, small working groups were organized in advance of the Workshop to prepare position papers. These papers served as the basis for Chapters 3, 4, and 5 of this report.

The chairmen and committee members of the Workshop working groups were the key to the successful dialogue and exchange of ideas. The chairmen for these groups were: Ray Jackson, Reflection and Thermal Infrared; Ted Engman and Chris Johannsen, Applications and Users; Thomas Schmugge, Microwave and Gamma Radiation; and Don Moore, Recommendations and Summary. The members of the working groups are listed in Appendix C, and their contributions are gratefully acknowledged.

The concensus of the Workshop committee on Recommendations and Summary are listed in Chapter 7. The Workshop members concluded that significant progress had been made in the development of remote sensing techniques for estimating soil moisture and that some useful applications for soil moisture information had been demonstrated to substantiate a research-oriented program for the development of an operational system for the remote sensing of soil moisture.

Special thanks are due to Ted Engman and his staff at the USDA-SEA Hydrology Laboratory who served as the hosts for the conference and Lynette Nelson of the Remote Sensing Institute at the South Dakota State University for her assistance in the organization of the Workshop and the preparation of the initial manuscript.

The recommendations and conclusions presented in this conference publication are those of the Workshop members and do not necessarily represent the policy and program direction of NASA and USDA.

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ACRONYMS

AID	Agency for International Development
ARS	Agricultural Research Service
AVHRR	Advanced Very High Resolution Radiometer
CCT	Computer Compatible Tape
CMI	Crop Moisture Index
CRD	Crop Reporting District
ERIM	Environmental Research Institute of Michigan
ESCS	Economic Statistics and Cooperatives Service
ESMR	Electrically Scanning Microwave Radiometer
EPA	Environmental Protection Agency
FDA	Food and Drug Administration
GIN	Green Index
GOES	Geostationary Operational Environmental Satellite
GSFC	Goddard Space Flight Center
HCMM	Heat Capacity Mapping Mission
HUD	Department of Housing and Urban Development
IMS	Irrigation Management Services
IR	Infrared
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LACIE	Large Area Crop Inventory Experiment
MAS	Microwave Active Spectrometer
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration

NESS	National Environmental Satellite Service
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
O/H	Office of Hydrology (NOAA)
OMB	Office of Management and Budget
SAR	Synthetic Aperture Radar
SCS	Soil Conservation Service
SDD	Stress Degree Day
SEA-FR	Science and Education Administration - Federal Research (formerly Agricultural Research Service)
SRS	Statistical Reporting Service
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USDI	United States Department of Interior
USGS	United States Geological Survey
WES	Waterways Experiment Station

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CHAPTER 1

FORMATION OF THE SOIL MOISTURE WORKSHOP

The need for repetitive soil moisture data over broad land areas has become apparent for such applications as crop yield forecasting, run-off prediction and general circulation modeling. Limited research programs related to remote sensing of soil moisture have been undertaken by the USDA, NOAA, USDI, and NASA using the reflected solar, thermal infrared, microwave, and gamma ray regions of the electromagnetic spectrum. To optimize the results of these investigations, a need for improved coordination of these research efforts was recognized. Similarly there is also a need for establishing lines of communication with potential users of soil moisture information to inform them of the current state of the art in soil moisture sensing. Recognizing these needs, NASA funded the Remote Sensing Institute of the South Dakota State University to organize a Soil Moisture Workshop to bring together the principal agencies and individuals who were investigating the remote sensing of soil moisture or who had soil moisture requirements. The objectives of the Workshop were to:

1. Evaluate the state of the art of remote sensing techniques
2. Examine needs of potential users
3. Make recommendations as to the future of soil moisture research and development

To accomplish these objectives small working groups (5 to 10 members) consisting of appropriate scientists, engineers and users were organized. Each group issued a position paper from their respective meetings. These position papers formed the basis for one-half day presentations at the Soil Moisture Workshop by each of the work groups.

The Workshop, held in Beltsville, Maryland on January 17-19, consisted of keynote speakers from USDA and NASA, three one-half day sessions involving presentations and discussions, and a summary and recommendations session to finalize the Workshop report.

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CHAPTER 2

REMOTE SENSING AS A TOOL IN ASSESSING SOIL MOISTURE

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The responsibilities of providing adequate food and fiber for future generations while conserving our soil, water, and air resources is of great concern to our national leaders and scientists. If we are to meet these responsibilities, the precision of our prediction capability has to be improved.

We will continue to live with a delicate balance between the supply of and the demand for essential food and fiber. This balance is so delicate that the variability in our normal climate can upset it. We will continue to have periods of excess rainfall which will be randomly interrupted by periods of rainfall deficiency. Half of our agricultural production comes from the semi-arid and arid regions where droughts are the most severe and frequent. The area also experiences seasons with excess rainfall.

A combination of low farm prices and drought can be disastrous. The "Dust Bowl" days of the Thirties are an important part of American history. The current unrest among farmers stems from low farm commodity prices and uncertainties associated with drought conditions similar to the Thirties.

Variability in precipitation accounts for the large recent irrigation development in this country. Irrigation gives the farmer and the banker security. Although only about 10 percent of the cultivated land in the U.S. is irrigated, about one-fourth of our gross agricultural income is from these lands. Every drought results in the drilling of additional irrigation wells and the depletion of reservoir water. The large well development is responsible for the groundwater mining that has occurred in this country. That agricultural demands account for 85 percent of the overdraft is causing the urban population and politicians concern. Every indication suggests the competition for water between the rural and urban communities will become more intense.

Because of an adequate supply of surface and ground water in the recent past, agriculture has not made the most efficient use of our water resources. Specialists in the field estimate that irrigated crops benefit from only about half of the water applied. The competition for water and the overdraft on our groundwater resources make it imperative that agriculture make more efficient use of water in the future.

Excess water can also upset the balance in our food and fiber production. Many of our serious plant diseases flourish during wet periods. Excess rainfall during the ripening stage and harvesting of our feed grains can reduce crop yields and quality appreciably. The wet period late in the 1977 season in Canada and the Northern

Plains caused reduced wheat yields and poor quality. An appreciable portion of the 1977 corn crop in the Southeast could not be marketed because of aflotoxins. Aflotoxins develop when the crop is subjected to prolonged wet periods after the grain has matured.

Yields on lands with poor surface drainage can be seriously reduced by crop innundations. Frequently, yields are reduced because of delayed planting on poorly drained lands. High rainfall at planting time also causes most of the erosion that occurs on these lands.

We urgently need better techniques for relating the impact of water stress or excess water on crop yields. The accuracy with which we can predict how too much or too little water will affect crop yields depends largely on how well we understand the interaction of soil water and plants. There is a real need for a better understanding of how too much or too little moisture affects crops at their different phenologic stages. When these relationships are understood, they can be reduced to a mathematical model. The effectiveness of these models must be confirmed by field data and the use of tools like remote sensing.

Soil moisture is the critical variable in all prediction models. It is basic to scheduling irrigation, to predicting runoff, and to forecasting soil erosion. The farmers schedule field operations based on soil moisture conditions. Agribusiness uses regional soil moisture data as a tool in developing their plans for the movement of fertilizer and pesticides.

Man has used remote sensing since the beginning of civilization. He climbed hills to scan for game. When he gained access to the small airplane, he periodically flew over his farm or ranch to survey his crops. When aerial photography became available, it was accepted rapidly by the agricultural community.

When satellite imagery became available, the photograph received an unbelievably hard sell. This hard sell promised a data base for solving most of the problems facing agriculture. In the past, many were impressed by the "pretty pictures." The fact that the payoff to agriculture from satellite imagery has been limited has caused some to become obsessed with the desire to deemphasize the satellite program. Congress and OMB plan to schedule hearings to gain a better understanding of the contribution made by space science. This information will be used to set budget priorities.

The Secretary of Agriculture has given crop prediction a high priority and has requested that research and action agencies provide more reliable and rapid methods for monitoring and predicting domestic and global crop conditions. If we are to meet the request, the Department has to have better mathematical models to work with. Confirmation of these models will require the input of remote sensing techniques. The capability of surveying large areas on a recurring basis is most important.

In the Department, the best known crop yield prediction project is the Large Area Crop Inventory Experiment (LACIE). In this experiment, satellite sensors are used to estimate the acreages planted to different crops. However, statistical and climatological yield prediction models are used to arrive at harvest figures. Therefore, LACIE does not yet have a remote sensing operationally implementable crop yield model. The models used depend on ground-based measurements and agronomic data.

For sometime ARS scientists have emphasized the need for a better understanding of crop response to such environmental stresses as moisture, temperature, and solar radiation. Recently, our administrators provided the resources to support these studies which will assess the importance of stress to crops at various phenological stages.

Although we are quite excited about the feasibility of measuring soil moisture by remote sensing, we recognize the problems involved. Albedo measurements can be used to delineate the three classical stages of soil drying, but use of this technique is limited to bare soil.

The use of microwave technology appears to be useful for measuring near surface soil moisture. This information is of importance to agriculturalists for predicting such things as wind erosion, crop germination, and water infiltration rates. Although microwave systems are experimental to date, there appears to be a good probability that data will become available in a format compatible with other data sources. While the all-weather capability of the microwave system has real appeal, the application of data from this tool does have limitations. Surface soil moisture can be ephemeral. Land surfaces have ground cover during most of the growing season. However, the assessment of crop stress for a combination of canopy temperature and albedo measurements appears to have great potential for predicting crop yields by remote sensing. This technique utilizes the innate ability of the plant to integrate soil and atmospheric moisture.

What can the scientific community do to ensure that agriculture gets maximum benefit from remote sensing? Firstly, it is important that the experiments be done by scientists with agricultural training and experience. I emphasize this point because we must understand a system before we can describe it. The plant response to water stress or water excess differs depending on the plant and the phenological stage. Plants reflect stress in different ways. Some crops, like alfalfa and beans become darker when deficient in water. Tobacco plants wilt when subjected to excess water for an extended time.

Secondly, interpretation of remote sensing data (from film or computer printouts) is not different in principle from the interpretation of other experimental data. Because of the area involved, however, ground truth validation can be very costly. A working knowledge of the soil resources can be a real asset for obtaining ground truth data.

Thirdly, most of the attempts to use remote sensing in prediction models has been to modifying existing models to take advantage of the capabilities of new sensor techniques. There has been sufficient success to convince scientists that remote sensing can be a good tool. The real benefits will come when prediction models are developed to take advantage of our capabilities in remote sensing.

It has been said that if we can land men on the moon there is no reason why we can't predict crop yields from satellites. However, science and technology in the problem-solving area is not looked upon as it once was. We have seen a new era of realism in political attitudes toward the problem-solving capability of research. The fact that the war on cancer, which was declared in 1971 and conducted at a cost of billions of dollars, is now recognized to have had a negligible effect on cancer survival rates creates a credibility problem for science. In the energy field, little credence is now given to the proposition that research and development are the keys to energy independence in the U.S. The once endless frontier associated with research is now regarded as very limited.

I am not saying that there is a mood of defeatism about research. I am saying that we must face reality and recognize that in applying remote sensing to agriculture we have problems of poor resolution, infrequent data, and slow data processing that have to be resolved. Landsat gets data every 18 days; crop growth, energy balance, and hydrologic models increment daily. The long periods required to acquire data tapes reduce their value in predicting yields.

Finally, I would like to identify a few high priority researchable problems in the remote sensing area. First, any procedure which could spectrally estimate ground cover would provide a tool badly needed in agriculture. One of the values would be for predicting crop yields and for providing "early warning changes" in the quantity and quality of our important crops. Methods for quantifying soil and atmospheric water and relating these values to crop performance would be invaluable. These water values would also be valuable for hydrological predictions. The quantification of water resources in storage on a routine basis should be rather easy to obtain and would be valuable to natural resource managers. Whether one is studying vegetation resources, crop production constraints, or aspects of the hydrologic cycle, there is a need for good weather data on a daily basis. Therefore, our cooperative efforts need the inputs of NOAA's meteorological satellite data applications program.

In summary, I think all of us are optimistic about the use of remote sensing data in agricultural decision-making. Few remote sensing programs in agriculture are operational, but several will be eventually. Agricultural scientists are now asking how remote sensing can be used to verify a mathematical crop model or test a hypothesis. The high cost of remote sensing research makes it imperative that NASA, NOAA, and USDA work together toward a common goal. I am confident that, if we can work together, remote sensing can contribute to the data base that will be required by tomorrow's farmer in his decision making.

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REMOTE SENSING OF SOIL MOISTURE

A NASA VIEWPOINT

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Since my field of specialization is not soil moisture, I hope you'll not take my comments as being those of a technical expert. Rather they should be interpreted as being from an individual who has had experience with many NASA technical programs. Carl is truly an expert in soil moisture and he has outlined many of the possible uses of such information. I will try to add a few points in terms of where NASA might be able to help by providing observational and information handling capabilities.

To determine how NASA could help, it is necessary to understand the function of the Agency. First of all, it should be recognized that NASA has no operational responsibilities for satellite observational systems. We are basically a research and development group. However, we want to develop space technologies that will be useful. As a result, meetings like this can be very helpful in terms of synthesizing the observational needs of a broad spectrum of users and providing guidance in terms of the areas in which it would be most beneficial for NASA to concentrate its research and development activities. The second point I want to highlight is that in addition to building space hardware, NASA has very active programs dealing with the processing and manipulation of data. These include programs aimed at putting data into forms useful for researchers or demonstration projects. For many programs, the efforts necessary to put the data into useful forms will be even more technically challenging than the building of the space hardware. As a final point, it is important that the applicability and usefulness of the data obtained be determined. In some cases NASA does this unilaterally but in many cases this requires close cooperation with other Agencies.

To date there have been a number of flights of observing instruments on both airplanes and satellites by NASA which have shown that it is possible with remote sensing instruments to make measurements which seem to be related to soil moisture. While the observations are generally also sensitive to other parameters, it appears that there is now a reasonable basis for optimism that remote sensing can be useful in making soil moisture measurements. These observations have been in the visible, infrared, and active and passive microwave areas.

The problem is to formulate a program which best meets the most important applications. Such potential applications could include: crop yield predictions, water runoff, farm management, climate forecasting, pest control, fire potential, extent of rainfall, plant disease prediction and wind erosion potential. To formulate such a program, it is necessary that for each application of soil moisture information the measurement requirements be quantified for system parameters such as: spatial resolution, temporal resolution, depth of measurement, accuracy of measurement, timeliness of data, format of data, and correlative information. The first four of these parameters are generally recognized; however, the last three are at least equally important and need to be recognized if the data is going to serve a useful function. Specifically, when the observing system is designed it is important that the plan include provisions for making the information available when it is needed and in a form which is useful for the particular application. Finally, it needs to be recognized that space observations only provide one source of data related to soil moisture. The total system should include the ability to incorporate the space data with the data obtained from other sources such as weather stations, geologic maps, ground truth test sites, etc.

With this information as background, it is clear that there are many questions which this Workshop should consider. First, should NASA initiate a program to further develop the ability to remotely measure soil moisture? While my personal opinion is that there is a basis for optimism that such a program could provide significant soil moisture information, you should assess whether this view is correct or whether other means of obtaining soil moisture information would be better. Secondly, if a development program is justified then what should be its objectives in terms of capability for measuring soil moisture? Thirdly, what are the initial and intermediate steps that need to be taken to meet these objectives? Finally, what types of research programs should be implemented that meld space and non-space measurements and study the resulting soil moisture measurement capability.

It is important in your considerations that you not look at just passive microwave, or just active microwave, or just infrared when considering the possibilities for making remote observations of soil moisture. It may well be that a multiple instrument observing system is best. The working group structure that has been established for this workshop tends to split microwave observations from visible and infrared observations. As a result, communications between the working groups may be appropriate to see whether a combined system might not be desirable. It is also important to recognize that in addition to any space observing system designed especially for soil moisture measurements, there are many other satellites in orbit that can provide information applicable to the soil moisture problem. Included are the NOAA and Landsat satellites. It may be that significant effort should be placed on getting the data from these other satellites into forms useful for soil moisture studies. The final point that I want to make is one that I have mentioned previously but wanted to stress again. It is that space observations are but one potential source of soil moisture information. We need to make sure that we do not focus only on the space observations when considering the soil moisture program.

With these comments, I hope you have a very productive workshop and thank you for your giving me this opportunity to express my views.

CHAPTER 3

APPLICATIONS OF SOIL MOISTURE INFORMATION

CONTRIBUTORS

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A. INTRODUCTION

The general consensus of the Application Working Group and those users surveyed is that soil moisture information is of significant value in a number of applications. Much of the user community can be identified as potential rather than present users of soil moisture information because of the current absence of data. It is difficult for users to clearly define their needs in terms of accuracy, resolution, and frequency. However, it is the consensus of users that once an operational program for acquiring soil moisture information is developed, numbers of users and applications will increase.

This paper discusses the needs of specific users within the areas of agriculture, hydrology, and meteorology. Sections are also included on the importance of drought, foreign needs for soil moisture information, some specific requirements for data information systems, and agency and organization uses of soil moisture.

B. DROUGHT

We know that a deficiency in plant available soil moisture reduces crop production, but precise definition of drought is difficult. There have been definitions of drought for nearly every discipline and it is usually defined in terms of how it affects a specific discipline.

An agricultural drought is concerned with soil moisture deficiencies related to crop yield. This varies depending upon the crops and the region where they are grown. If irrigation water is available the economic impact of drought will be reduced.

A hydrologist will think of drought as a deficiency in precipitation or runoff. He may consider this in terms of a decline in ground water levels or in the amount of water held in a reservoir. The measurement will usually be in terms of a deviation from a normal, a relationship which is found in most definitions.

A meteorological drought will be concerned with a deviation from the normal climate such as the amount of precipitation received compared to the normal or mean precipitation for that location. Systems or indices such as the Palmer Drought Index have been used to classify drought severity using the difference between actual monthly precipitation and that required to meet the demands of evapotranspiration. Both the duration and the magnitude of the abnormal moisture deficiencies are considered.

A drought becomes recognizable only after a period of time has passed. The termination of a drought is almost as difficult to detect as the beginning since it may be temporarily interrupted by one or more short precipitation periods. A knowledge of soil moisture at any given time by location becomes extremely important when discussing drought and determining its potential and actual impact.

C. AGRICULTURE

Soil moisture as mentioned earlier is important to the growth of all vegetation. As we consider the growth of cultivated crops, range, and forest, soil moisture is considered directly or indirectly by many different users in each stage of their production. Agricultural crops have optimum soil moisture regimes. Drought or excessive moisture deviations from those optimum levels will reduce immediate and future yield, increase possible damage and losses from pests, and may result in the complete loss of the crop.

1. Crop Production

Approximately 20% of the land area in the United States is utilized for cultivated crops. Production of crops has become extremely important in foreign trade and the balance of our nation's trade deficit.

Table 3-1 presents eight distinct stages of crop production that are affected by soil moisture. The soil moisture conditions at each stage and the users of the information are listed. Only the primary users have been identified since most agricultural related industries, agencies and producers utilize the information of each production stage at one time or another.

During the growth and development stages, the farmer or producer is concerned with a number of practices which he uses to stimulate growth, quality and yield of his crop. Some of these practices include fertilization, water management which includes both irrigation and drainage, and cultivation and/or harvesting operations. The control of pests such as weeds, insects or pathogens has fostered a number of

Table 3-1. Soil Moisture Conditions at Different Stages of Crop Production and Interested Users at each Production Stage.

Production Stage	Soil Moisture Conditions	Users
Planning (Acreage & Yield Predictions	Estimates of plant available water being received in winter months for a time period prior to planting. Yield prediction models will utilize soil moisture by the week through the growing season.	Producers, Policy-makers, commodity markets, transportation, storage, agricultural input industries.
Ground Preparation & Planting	Trafficability for farm equipment. This information needed on an area-regional basis.	Equipment and repair parts manufacturers, chemical industries
Germination	Adequate moisture for seed germination is needed. Information on too little or too much moisture is important.	Producers, seed companies, chemical industries.
Growth and Development---		
Nutrient supply	Adequate moisture flow needed for root uptake. Too much moisture affects roots and causes loss of nutrients (anaerobic conditions and leaching)	Planning users, especially fertilizer industry.
Water management irrigation	Plant stress indicates need for irrigation. Need to determine efficient use of available water. Limited water-need to determine most advantageous time to apply.	Irrigators and water planners.
Water management drainage	Waterlogged soils cause anaerobic conditions which affects nutrients, root respiration, etc.	Producers, drainage districts.

Table 3-1 Continued

Production Stage	Soil Moisture Conditions	Users
Pest Management		
Weeds	Weeds take moisture from economic plants. Soil moisture conditions need to be known for best incorporation of herbicide	Producers and chemical industry
Insects	Soilborne insects need adequate moisture for reproduction cycle. Insecticide application and incorporation are dependent on soil moisture	Producers and chemical industry
Pathogens	Soilborne pathogens need adequate moisture for reproduction cycle. Fungicide application and incorportation are dependent on soil moisture	Producers and chemical industry
Maturing-(Yield Estimates)	Need to know moisture at specific stages of growth. Some stages have more influence on yield than others. Need also predicted moisture or precipitation.	Policymakers, commodity markets, transportation, storages, agricultural input industries.
Harvest	Trafficability of harvest equipment dependent on soil moisture. Vulnerable at excessive moisture not only to inability to harvest but to lodging and quality deterioration due to increase in pathogens and insects.	Producers, equipment industries, transportation, storage

industries which not only supply the chemicals but also custom apply them for the producer. All of these management practices are related to the soil moisture conditions because soil moisture determines when the practices are most efficient.

Data and information requirements for soil moisture are variable at the different production stages (Table 3-2). Highest accuracies are required during yield estimates, irrigation scheduling and pest control. More frequent coverage at a higher resolution is required when greater economic gains or losses are at stake.

Table 3-2. Soil Moisture Information and Data Requirements at Different Crop Production Stages

Crop Production Stage	Accuracy Level*	Frequency (Days)	Resolution (km^2)
Planning (Acreage & Yield Predictions	3-5	7-20	1-15
Ground Preparation & Planting	1-3	5	.5-1
Germination	3	5	1-10
Growth & Development			
Nutrient Supply	3	7-10	1-10
Water Management-Irrigation	5	3	.5
Water Management-Drainage	3	3-5	1-10
Pest Management	5	3	.5
Maturing-Yield Estimate	3-5	3-10	.5-1
Harvest	3	3-7	.5

* 1 = General accuracy of High, Medium or Low

2-4 = Gradation between accuracy level 1 and 5

5 = ±4% accuracy by value measurement

Leaching of soil nutrients, deposition of saline or alkaline deposits, and flushing of agricultural chemicals in surface runoffs are of concern because of their impact on the environment. Movement of herbicides, fungicides and insecticides within the soil water are also a direct economic concern to the farmer. More accurate soil moisture measurements would assist in better planning to reduce their losses.

2. Range Production

About 40% of the land area in the U.S. is suited or used for pasture and range production. Some of the same practices or production stages listed in crop production are of interest to range managers and to wildlife managers. Ground preparation and range reseeding, brush removal programs, scarification and other practices are used to prepare seedbeds that encourage germination and growth of desirable forage plants. At the same time some of these practices discourage the growth of undesirable species such as weeds and poisonous plants. The range producer should be concerned with the problems of erosion and soil damage which can result during ground preparation and planting phases if the soil is too wet (soil compaction, puddling, etc.) or too dry (wind erosion).

Range and wildlife managers may use a number of techniques such as timing of herbicide application to control poisonous or noxious plant species. Deferred grazing is used to prevent compaction damage to wet soil to permit the germination of desirable species. Practices such as salting, fencing and water imrpovements are used to distribute grazing more evenly.

3. Forest Production

About 30% of the U.S. land area is utilized for timber related uses. Many aspects of the production stages listed under crop production will also apply to timber production. The forester will be concerned about soil moisture conditions suitable for ground preparation and planting twice in one crop cycle. Seedlings are frequently grown in nurseries where the nurseryman faces problems in seedbed preparation and adequate soil moisture conditions for germination and seedling survival. A few years later the seedlings are transplanted. In suitable terrain, planting of the seedlings is a mechanized operation involving trafficability problems for tree planters. They also must remove enough existing vegetation that the seedlings can compete for sunlight, nutrients and soil moisture.

The forester may not only irrigate and fertilize in his nursery but will also apply pesticides to control competing brush, weed trees, insects and diseases. Applications must be timed to critical periods in the life cycles of the pests which are frequently dependent on soil moisture, temperature and plant phenological stage.

4. Pest Management

Pest management has been discussed in terms of crop production but there is another important aspect which deals with public and animal health. Some pests follow a life cycle that depends on soil moisture and temperature conditions. Altering these conditions to any extremes will disrupt their life cycle.

The effect of shallow water bodies and the increase of mosquito production and its effect on public health is a familiar one. The increase of the screwworm and its effect on cattle production in the southwest is an example of concern for animal health.

There are a number of users which are concerned about conditions which affect pest epidemiology including the World Health Organization, Public Health Service, Food and Agricultural Organizations, Agency for International Development, and state veterinarians.

The Environmental Protection Agency has increased its regulations covering the use of pesticides. In terms of pest management for crop production, all applicators of any pesticides for commercial purposes must be certified. In addition to farmers and chemical manufacturers and dealers, other user groups that have an interest in soil moisture information as it affects pests are the Regional and Environmental Science Centers of NOAA, a number of agencies within USDA (Extension Service, Statistical Reporting Service and Agricultural Research Service), aerial applicators, and farm broadcasters.

5. Soil Classification

Soil classification is called soil taxonomy and is a hierarchy system wherein soils are divided into orders, suborders, great groups, subgroups, families and series. Soil moisture regimes are a very important part of soil taxonomy. Soil moisture regimes are defined in terms of the ground water level and the presence or absence of water held at a tension of less than 15 bars of atmospheric pressure in the root zone.

The "aridic" and "torric" moisture regimes are normally found in very arid climates. Aridosol is one of ten orders in the soil taxonomy system which describes dry soils. Therefore the distinction of dry soils has been considered extremely important since it is described at the highest level of the soil taxonomy system.

The "aquadic" (wet) moisture regime implies a reducing regime that is virtually free of dissolved oxygen because the soil is saturated by ground water or by water of capillary fringe. The "udic" moisture regime implies that in most years the soil moisture control section is not dry in any part for as long as ninety consecutive days. "Ustic" moisture regime is an intermediate between aridic and udic regimes. The concept is one of limited moisture but the moisture is present at a time when conditions are suitable for plant growth. The "xeric" moisture regime is that typified in the Mediterranean climates where the winters are moist and cool and summers are warm and dry. In all of these moisture regimes, there are variations of temperatures. These moisture regimes are found in the suborders of soil taxonomy. Descriptive terms referring to these moisture regimes are found throughout the other classification categories.

Soil moisture is an important factor in the mapping of soils and their classification. Soils are being mapped under the National Cooperative Soil Survey programs to determine the location and extent of different soils and the properties important to their use. Soil maps with interpretations are used by farmers to determine what crops are most suitable, by planners for locating areas to their best use, by builders concerned with soil properties that affect their structures, and many other users.

A soil scientist will map soils by identifying distinct properties that characterize each separate soil series. The series may have a phase modifier which represents an additional important characteristic of that soil. Therefore a soil series may typically be well drained but could also have a somewhat poorly drained phase. These phases are referred to as soil drainage classes. Soil drainage classes are very poorly drained, poorly drained, somewhat poorly drained, well drained, moderately well drained and excessively drained. Specific criteria are utilized to separate each of the different drainage classes.

It should be noted that soil moisture, soil water movement and soil drainage are related to soil texture (texture is defined as the size of individual soil particles). Coarse textured (sandy soils) generally drain faster and dry quicker than fine textured (clay) soils.

6. Wetland Inventory

The U.S. Fish and Wildlife Service has begun an inventory of wetland and aquatic habitats of the United States. Since 1975, an extensive effort has been undertaken to develop a system which could categorize wetlands on a national scale. Previous classification systems were applied on a regional basis.

For the new classification system, wetland is defined specifically as land where the water table is at, near, or above the land surface long enough each year to promote the formation of hydric soils and to support the growth of hydrophytes as long as other environmental conditions are favorable. Permanently flooded lands lying beyond the deep water boundary of wetlands are referred to as aquatic habitats.

Detection and measurement of water and soil moisture are extremely important to the wetland classification system.

D. HYDROLOGY

The hydrologist is concerned with precipitation, irrigation, infiltration, runoff, and evapotranspiration. There are many factors pertaining to the hydrologic cycle (Fig. 3-1) that are closely related to soil moisture. The land surface and soil blocks as shown in Fig. 3-1 affect all aspects of water movement except when the atmosphere and water bodies interact directly. Soil moisture is important because it affects the rate and capacity of water movement in the land surface and soil.

Several important stages of the hydrologic cycle were explored for their importance to user clientele. The accuracy needs, frequency of coverage and resolution requirements of the users were estimated (Table 3-3). Further discussion of the data requirements are found in a separate section at the end of the paper.

1. Runoff Potential

The National Weather Service of the National Oceanic and Atmospheric Administration has the primary responsibility for flood hazard warnings. However, flood-flow measurements by the U.S. Army Corp of Engineers and the U.S. Geological Survey of the Department of the Interior are reported to forecasters to aid in the warning system. Current methods of runoff prediction depend on adequate separation of the precipitation into infiltration, runoff, and surface storage.

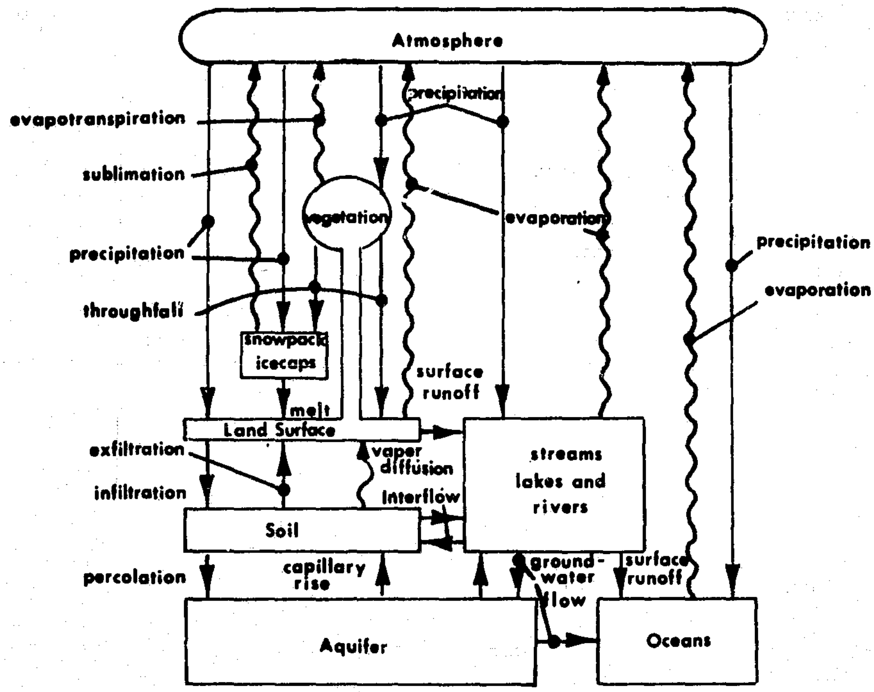

Fig. 3-1. The hydrologic cycle from an engineering viewpoint (after Eagleson, 1970).

Table 3-3. Needs of Soil Moisture Information and Data Requirements in Hydrology.

Soil Moisture Applications & Identified Users	Accuracy Level*	Frequency (Days)	Resolution (Km^2)
•Runoff Potential:			
•Federal Users: NOAA-NWS, USACE, SCS design engineers, USBR, HUD Flood Insurance Program	1**	3-7	5-25
•State Users: Highway Departments and Water Resources Centers			
•County and City Governments			
•Private Power Companies			
•Erosion Losses:			
•Federal Users: Design Departments of USACE, USDI and USDA-SCS	3	3	5-25
•County Organizations of Governments	5	3	.5
•Farmers Organizations	3	3	1
•Reservoir Management:			
•Federal Users: USACE, USBR	1	3-7	5-25
•State and Local Users: Water Resources Centers	3	3-7	.5
•Private Power Companies, regional planners, recreation industries	3	3-7	.5
•Infiltration for Trafficability and Structure Design			
•Federal Users: USACE, USDA-SCS	5	3	.5
•State Users: Drainage Districts, Planners	5	3	.5
•Private irrigation design engineers, mining engineers, developers	5	3	.1
•Water Quality			
•Pesticide and Nutrient Losses:			
•Federal Users: EPA, FDA, USDA-SCS	5	3	.1
•State Users: Water Resources Centers	3-5	3	.1-.5
•Private irrigators, farm organizations, feed lot operators, hydrologic engineers, planners and developers.	1-3	3-7	5

* 1 = General accuracy of High, Median and Low
2-4 = Gradation between level 1 and 5
5 = ±2% accuracy by volume measurement.
** = Data refer only to the users on the respective line in the table

Forecasting models require accurate estimates of soil moisture or antecedent precipitation as an index of soil moisture. Forecasts as well as predictions of runoff from ungauged watersheds should be improved with reliable estimates of soil moisture. These same models are used to establish design criteria for dams, bridges, culverts, and channel control devices. Improvement in the prediction capability of the models will result in improved design that can save construction costs and improve water quality.

2. Erosion Losses

Estimation of erosion and sedimentation transport is a primary concern of design engineers. When present techniques are used, sedimentation yield is attributed to soil losses from fields and from bank erosion and gullies. Moisture conditions in the soils affect the weathering processes and the ultimate supply of sediment to the stream. However, the runoff process, which is affected by soil moisture, is the primary mechanism for erosion and sediment transport. Unfortunately, present design procedures have not been developed to the point where soil moisture is used in calculating erosion and sediment transport.

Measurement of soil moisture combined with remote sensing data that measure the extent of gulley area could enhance the prediction of sediment transport into the water storage structures and sediment traps. The need for production control is primarily in the upstream drainage systems. Builders of dams for flood detention or power supply are very concerned with predicted volumes of sediment. Sediment transport is also a concern to those responsible for water quality since pesticides are transported by sediment particles.

3. Reservoir Management

Reservoir management models depend on runoff models that calculate inflow to the impoundment. Improvement in water runoff prediction with additional soil moisture data will improve the management mode but new models that can incorporate soil moisture data must be developed. The allotment of the water for specific uses is very dependent on the amount of water in the reservoir and that which can be predicted.

4. Infiltration

Infiltration rate or rate of depletion of surface soil moisture is a critical soil interpretation used by those developing irrigation systems, predicting watershed runoff, determining ground water recharge, etc. These rates must be known before any water balance model can be updated effectively. Almost all infiltration models have one or more parameters that are dependent upon the soil moisture before water application. Drying rates also determine how early soils can be subjected to tillage or heavy traffic. Time series of soil moisture measurements can be used to help determine these rates.

5. Water Quality

Water quality monitoring and management are the responsibility of many federal agencies with the Environmental Protection Agency setting the standards to be followed. The agencies must seek EPA's approval of proposed work that may influence water quality. The movement of water in soils can transport pollutants and nutrients into the ground water supply. Modelling soil water movement requires a reliable measure of soil moisture. It should be mandatory that soil moisture measurements be related to more than one depth level to develop more precise models.

Most water quality analysis depends upon runoff from the land surface or percolation out of the root zone. The influence of soil moisture here is indirect through its control of the rate of runoff. However, soil moisture does have a direct influence on the rate of the mineralization of nitrogen which can affect efficiency of nitrate fertilizer applications. Excess fertilizer may end up as a pollutant in a waterway or the groundwater.

E. CLIMATE AND WEATHER

The ability of soil to store water and release it through evapotranspiration is important in climate forecasting. Much of the precipitation that falls in the interior of continent originates on land. Thus, soil moisture anomalies in the root zone can affect regional climate for an entire growing season.

Evapotranspiration is the combined loss of water through the process of evaporation and transpiration. Many methods exist for predicting or measuring evapotranspiration; a compilation of the various estimation techniques is given in a treatise by Jensen (1975). Evaporation may occur from water surfaces or bare soil while evapotranspiration occurs when a canopy is present on the surface.

Idso et al. (1974) described the various stages of evaporation from a bare soil surface. During first stage when the surface is wet, the rate is limited only by the availability of energy to the surface. As the surface dries the rate decreases and is controlled by the transfer of water to the surface. The length of time between stage 1 and 3 evaporation depends on the surface soil moisture and the energy available to the surface. Therefore, the rate of soil evaporation depends upon the soil moisture content.

Evapotranspiration from a canopy depends on the soil moisture available in the volume of soil occupied by active roots, the type of canopy, and the energy input to the system. There are only a few methods which accurately predict evapotranspiration with limited water availability (Jensen, 1975; Kanemasu et al., 1976). Soil moisture supplies control the rate of water supply to the roots but the canopy controls the rate of water loss to the atmosphere through stomatal regulation.

Of the evapotranspiration models that are available few are applicable over large regions and few account for the soil moisture in the profile except through a soil moisture balance. Research is needed in the following areas:

* Spatial variability of soil moisture in the field and its effect on the integrated evapotranspiration for the field.

* Evapotranspiration models which are applicable to large regions.

* Experimental procedures for defining the spatial and accuracy requirements.

The accuracy and spatial resolution requirements vary for each application. For individual fields the accuracy of soil moisture may have to be 2 to 3% (volume basis) for the upper two meters of the soil profile and the spatial resolution on the order 5 to 10 m^2. For large regional applications the accuracy may be relaxed to 5 to 10% (volume basis) for the upper two meters of the profile and the spatial resolution to 10,000 m^2.

F. FOREIGN USES OF SOIL MOISTURE INFORMATION

The economy of the United States is tied very loosely to that of other developed nations, and with many important and long-range trade aspects of developing nations. Soil moisture information can be utilized in similar ways in other developed nations as has been discussed for the United States. For developing nations, the importance of soil moisture data is in the prediction of current food production and assistance of agricultural land development.

The importance of accurate weather predictions and soil moisture supplies has been recognized by such projects as the Large Area Crop Inventory Experiment (LACIE). The initial planning phases of any project of land development require reliable data on soils, vegetation, water and other resources. Soil moisture can, as shown in previous sections, influence crop selection, timing of planting, and crop yields, but the decisions are of a more primary concern. Current reliable data also have an influence on the location and method of infrastructure development.

Since the passage of Title XII Act of 1976, U.S. Land Grant Colleges have taken a more aggressive and realistic role in foreign agricultural development. The need for planning information including soil moisture status, would be extremely helpful to these programs as well as to ongoing programs of foreign governments, Food and

Agricultural Organization, Agency for International Development, foundations and private development financiers.

G. DATA REQUIREMENTS

Three important criteria in providing soil moisture information are timeliness, accuracy and adequacy of coverage. Many users when asked about their requirements of these criteria will reply that they need the information as accurately and rapidly as possible with updates every few days. When one really presses the user there are some important aspects that should be considered when developing data acquisition systems.

Most users like to be alerted to deviations from the expected or the normal as soon as possible. Initial announcements need not be extremely accurate, but the alert of a problem is important. This is especially true for crop conditions, low water supplies, changing temperatures and other potential problems that affect many users. Therefore, timeliness of information is more important initially than accuracy.

After the alert of a problem, refinement of a specific answer should begin. Most users are quite tolerant of a week's time in obtaining that refinement. Decision makers are already looking at a number of options and will make the decision of which option to follow when specific data has arrived or when a time period has been reached where a decision must be made.

Measurements or estimates of surface soil moisture are of little value to agriculture. Data are needed for depths of at least 1 meter and preferably 2 meters. This is the zone of maximum root accumulation and therefore water uptake by the plant.

H. AGENCY/ORGANIZATION USES

Following are summaries of uses of soil moisture information and activities related to soil moisture that were submitted by various agencies and organizations.

1. Forest Service

The Forest Service uses soil moisture information in three major areas as follows:

* Soil moisture as related to plant growth
  - time of planting for forest regeneration, range seeding, etc.
  - species selection
  - site productivity
* Soil moisture and hydrologic relationships
  - predicting soil runoff, flood and erosion hazard
* Soil moisture and soil mantle stability relationships
  - road construction and other engineering activities

In all three areas the Forest Service needs the ability to determine and/or predict the soil moisture content at a given time.

Presently the Forest Service uses soil moisture regimes, identified by direct moisture measurements, to predict soil moisture content at a given time. Because on-site measurements are costly and time consuming, the Forest Service more often estimates soil-moisture regimes on the basis of the type of natural vegetation on the site.

2. Statistical Reporting Service (SRS)

Soil moisture is undoubtedly very important in its effects on crop yields. SRS has a definite interest in soil moisture because the agency estimates and forecasts crop yields. At maturity, crop yields can be measured and estimated directly from sample surveys. Forecasts, when crops are approaching maturity, can also be based upon direct crop measurements as "interpreted" through appropriate forecasting models. Use of physiological models which incorporate soil moisture among other variables are therefore of greatest potential value in providing early to mid season forecasts. Currently several physiological models are being evaluated. All depend to some extent on soil moisture. If the utility of any of these models is proven and if they are adopted as an operational method, SRS could utilize more comprehensive soil moisture information. However, present needs for SRS soil moisture information are limited to specific research sites.

3. Soil Conservation Service (SCS)

The Soil Conservation Service is interested in soil moisture as it relates to drought and soil classification. To aid rural drought disaster or potential drought areas, SCS needs improved knowledge of soil moisture. If SCS could deliver useful information on the spatial extent of drought conditions and probable future moisture availability, better resource management decisions could be made. The principal drought related needs of SCS are:

* A system for drought forecasting that allows the government time to gear up with assistance programs

* A signal whereby SCS can adjust its operation to focus on drought related assistance

Soil moisture needs of SCS related to soil classification are:

* Water content at saturation by family
* Saturated and unsaturated hydraulic conductivity by family.

Some present and proposed soil moisture studies include:

* A study to determine moisture status and temperature of dry soils in the southwest to determine the length of time the soils are dry to aid in classification
* A study of the physical properties of soils in watershed hydrology
* A survey conducted by the National Soil Survey Laboratory to study effects of paralithic contacts on hydraulic conductivity
* A planned soil moisture study in eight of the major agricultural regions in the U.S. to verify and improve soil moisture models for determining and evaluating wetness and drought, and to improve soil classification with respect to moisture regime
* An agreement with the Agricultural Research Service to expand a site specific watershed evapotranspiration model to an area wide evapotranspiration model

4. <u>Agricultural Research Service (now SEA-FR)</u>

The Agricultural Research Service, in its research capacity, is interested in soil moisture because of its importance to:

* Physiological processes of crop and range plants that affect growth and yield

* Irrigation requirements and scheduling
* Hydrology -- especially runoff, erosion, and water supplies
* Drought, drainage needs, trafficability, habitat of insects and pathogens
* Land suitability and capability

5. U.S. Bureau of Reclamation (USBR)

The Division of Water Operation and Maintenance of USBR requires soil moisture and related information for wide-area application of its Irrigation Management Services (IMS) program. The goal of IMS is to achieve optimum operation of entire irrigation projects. The IMS program presently includes portions of 26 irrigation projects in 12 western states and involves field-by-field irrigation scheduling and operational coordination of farm water demand throughout irrigation projects' storage and distribution systems. Several functions are performed periodically (daily, bi-weekly, etc.) including monitoring soil moisture using neutron probes, tensiometers or similar equipment; computerized water budget analysis of evapotranspiration and consumptive use; and accounting of irrigation and cropping patterns. Soil moisture and related information needed for application of IMS include:

* Identification of land mass receiving irrigation
  - total irrigated vs. non-irrigated acreage
  - crop identification and acreage
  - field boundary mapping
* Surface moisture conditions (indication of recent irrigation or precipitation

* Crop growth stage
* Cultural operations (periodic harvesting of alfalfa)
* Identification of areas of crop stress
* Identification of drainage problem areas and high water tables

The Hydrology Branch of the Division of Planning Coordination has the following soil moisture and related requirements:

* The ability to identify farms and fields receiving irrigation water
* Coverage, depth, and water content of snow
* The soil moisture condition of a drainage area prior to snow coverage
* The soil moisture condition of a drainage area before and after a precipitation event
* The soil moisture condition of a drainage area before and after a flood
* The soil moisture condition of a field at the beginning and end of a growing season
* The soil moisture condition of irrigated fields at the head and lower ends after irrigation

The Land Utilization Section of the Resource Analysis Branch is interested in soil moisture because of its importance in economic land classification for sustained irrigation. Planning studies for water and land resource development include determining moisture retention properties, infiltration characteristics, and permeability conditions of soil. In addition to direct soil moisture considerations, land classification is also concerned with related conditions of soil salinity, root penetration, and aeration within the root zone.

6. <u>U.S. Geological Survey</u>

The Water Resources Division of USGS is conducting several research studies that include soil moisture as a variable. Although soil moisture needs are somewhat peripheral to most of the water resource investigations, a number of hydrologic studies require soil moisture information. Current activities related to soil moisture are:

* A study of the dynamic movement of water from the soil surface to an aquifer. The hydraulic characteristics of the soil types and the availability of the water to move through the soils are of primary concern.
* A study devoted to development of ground water supplies and soil and water conservation for public land. If the degree of soil wetting or moisture depletion can be determined synoptically and at frequent intervals, the information would be useful for management decisions on use of resources of the arid west.
* Development of model for runoff analysis. Volume and timing of surface runoff from rainfall or snowmelt are influenced by soil moisture conditions immediately preceding the event. These antecedent soil moisture conditions vary temporally and spatially, and include factors such as slope, aspect, soil type, and vegetation type and density.
* A study of erosion and sedimentation

* Wetlands studies. Although wetland soils are often saturated, some fringe areas may be dry during certain times of the year, and these dynamic conditions may be important in understanding wetland hydrology.
* National water-use inventory. The Water Resources Division has been directed to conduct a national water use inventory that includes domestic, agricultural, and industrial uses. One of the more difficult aspects of the inventory is identification of irrigated areas.
* A study of water movement in karst terrain and fracture zones. Remote sensing, particularly thermal imagery, has been used to identify sink areas in karst terrain, and to study water movement through fracture zones.

7. Army Corps of Engineers

The Waterways Experiment Station of the Corps of Engineers is interested in soil moisture monitoring and forecasting because soil moisture has a major influence on performance of different types of military vehicles and is a factor in estimating stream levels and predicting flooding. For military application, estimating soil moisture without recourse to in situ field measurements is desirable.

In the late 1940's the Waterways Experiment Station (WES) began studies on mobility of military vehicles. It was obvious that soil moisture to a depth of about 12 inches had a major influence on soil strength and vehicle mobility. Mobility studies are still underway and it appears that reasonably accurate forecasts of soil moisture will be possible utilizing a soil moisture model with information from meteorological monitoring and forecasting, and remote sensors.

Recent developments in computers, mathematical modeling and remote sensing have added a new dimension to hydrology. The Waterways Experiment Station is presently conducting a study in military hydrology which is intended to improve the hydrologic capability of the armed forces. The major difference between military and civilian hydrology is the restrictions on access to the watershed under military operation, making remote sensing an essential aspect of the study. It is felt that a soil moisture model compatible with remote sensing systems will be necessary to estimate moisture as a function of depth and to forecast soil moisture conditions throughout the watershed for several days in advance.

8. Agency for International Development (AID)

AID is interested in soil moisture as it relates to drought and desertification in developing countries. Lack of rain, shifting winds, and overgrazing are among the factors that contribute to desertification. If the drought that affected the Sahel in Africa could have been anticipated, arrangements could have been made earlier to supply and distribute food to the affected areas. Thus, AID is interested in development of remote-sensing techniques to anticipate the need and supply food to drought affected areas. Soil moisture is one of the parameters that is important in drought monitoring.

9. NASA

As part of the LACIE program, NASA/JSC is interested in improving yield technology through soil moisture sensing. At the present time the capability exists to run some soil moisture budget models using ground meteorological data. What is needed is an improvement over the current state of the art. Soil moisture estimates are required not only for bare soil, but for a developing canopy as well. Preliminary LACIE yield model/soil moisture requirements are as follows:

* Soil moisture profile measurement requirements
  - resolution between field size and $(15\ \text{km})^2$ grid
  - water content to within ±10 percent of value with specification of depth of water
  - depth of profile to beneath root zone
  - repeat every 18 days to update soil moisture models to more frequent repeats if dictated by integration with yield models
  - soil moisture yardstick invariant through crop season, canopy, tillage variations, topographic difference, time of day
* Detailed requirements are being developed through assessments of performance of competing yield modeling approaches.

NASA/GSFC, in response to the Interdepartmental Committee for Atmospheric Sciences report A United States Climate Plan, has developed a plan for using NASA observational capabilities to advance practical understanding of the behavior of climate systems. The climate spectrum has been divided into four separate but interrelated portions:

* Current state of the climate
* Regional climate which occurs on a time scale longer than a month but shorter than a decade

* Climate which occurs on time scales of a decade or longer
* Climate produced by man's activities on all time and spatial scales.

The ability of the soil to store water and release it through evapotranspiration is important in climate forecasting. Soil moisture requirements of the NASA Climate Program are summarized in Table 3-4.

Table 3-4. Soil Moisture and Related Requirements of the NASA Climate Program

Parameter	Desired Accuracy	Base Requirement	Spatial* Resolution	Temporal* Resolution
Surface soil moisture	0.05 cm^3 H_2O/cm^3 soil	4 levels	500 km	1 month
Soil moisture (root zone)	0.05 cm^3 H_2O/cm^3 soil	4 levels	500 km	1 month
Evapotranspiration	10%	25%	500 km	1 month
Plant water stress	stress/unstressed		500 km	1 month

*The values for the spatial and temporal resolutions were determined by current model inputs, finer resolutions may be required to obtain these data.

10. NOAA

NOAA's primary interest in soil moisture is to improve infiltration estimates so that runoff and water supply can be computed more accurately. The Office of Hydrology (O/H) within the Weather Service is responsible for providing river and water-supply forecasts for the United States. To meet these requirements mathematical models are used to provide river stage forecasts based on various watershed and hydrometeorological parameters. Soil moisture is one parameter that could significantly improve river and water-supply forecasts. Research at the O/H currently involves gamma-ray data, collected by aircraft, to obtain averaged soil moisture values and a theoretical accounting approach to soil moisture.

Research at NESS combines aircraft and ground measurements with various types of satellite-acquired data (microwave, thermal and near-IR and visual) to find techniques that can provide basin-wide estimates of soil moisture. Our program involving soil moisture began in 1970 at Tempe, Arizona, under a contract with Aerojet Electrosystems. The study measured, via ground-based radiometers, the effect of varying soil moisture content of bare soil on microwave brightness temperatures. Later studies used airborne passive radiometers to obtain data from sparsely and heavily vegetated areas in Arizona and New York, respectively.

Results from these surveys indicated that changes in soil moisture from bare or sparsely vegetated fields can be detected, particularly at soil moisture levels above the wilting point, using the longer wavelength radiometers (6 and 21 cm). The analysis of microwave data from heavily vegetated test sites near the Finger Lakes in New York was inconclusive due to heavy thunder showers that fell between overflights leading to significant changes in the microwave characteristics of the terrain owing to the variable soil moisture conditions.

Gamma radiation is attenuated by water, hence the attenuated gamma-ray signal from naturally occurring radiation in the ground is an inverse function of soil moisture. Experiments in Arizona have been conducted for NOAA by EGG, concurrently with the microwave experiments under the direction of NASA/GSFC. Results were in general agreement with soil-sampled data. Unfortunately the gamma-ray technique is limited by atmospheric contamination of the signal and the data must be obtained from low-flying aircraft (150 m). A further limitation is the necessity of first calibrating a given area before useful data can be obtained.

The percent reflectance of wet soils is usually about 10 percent less than the percent reflectance for dry soils, with the greatest difference in the near-IR (0.7 to 1.0 μm). A study funded by NOAA (Earth Satellite Corp.) looked at Nimbus-3 near-IR data from the high-resolution infared radiometer. It was possible to detect, in a gross way, wet areas following 24-hour rainfalls exceeding 2.5 cm. Landsat MSS data of fields west of Phoenix, Arizona, showed an inverse relation of soil moisture to reflectance for bare fields in both the visible and near-IR portions of the spectrum. However, vegetated fields showed a direct relation between soil moisture and reflectance in the near-IR but no change in the reflectance in the visible (0.5 to 0.6 μm and 0.6 to 0.7 μm).

The ultimate objective of the NOAA/National Environmental Satellite Service (NESS) program of remote sensing of soil moisture is to develop a satellite sensor to measure soil moisture in large river basins to improve flood and water-level forecasts. At present the long-wavelength passive microwave radiometer looms as the best potential sensor. However, before passive microwave techniques are used operationally to assess soil moisture quantitatively, additional theoretical work and basic data collection need to be made.

11. <u>Jet Propulsion Laboratory</u>

Areas where progress must be made for obtaining quantitative soil moisture information from satellites are:

* perform well calibrated aircraft and ground-based studies to improve the basis for deriving empirical models of effects of roughness and vegetation cover.
* Improve current theoretical/empirical models to optimize system design parameters, develop data interpretation techniques, and increase the accuracy of soil moisture estimation.
* Investigate multiple sensor approaches, data analysis techniques, and associated problems.

JPL has planned a joint microwave/thermal infrared soil moisture program to contribute to the above-mentioned areas of interest. The JPL four-frequency ground-based microwave radiometry system, and infrared and micrometeorological equipment will be used to collect data from fields in the San Joaquin Valley area of California.

12. Kern County Water Agency

The Kern County Water Agency in Kern County, California, has cooperated with various universities and organizations in evaluation of phenomena related to soil moisture, particularly in evaluating problems related to drainage. Some of these studies and activities are:

* Monitoring development of perched water tables
* Evaluating crop damage within drainage problem areas
* Landsat-aided evaluation of water demand
* Radar study of soil moisture
* Thermal study to establish surface thermal properties and soil moisture profiles
* Landsat evaluation of crop stress and crop damage.

I. KEY-POINT SUMMARY

* Present and potential users consider soil moisture information to be very important
* Uses and applications of soil moisture information will expand once an operational system is developed
* Very few present and potential users of soil moisture information can define their data needs in terms of accuracy, resolution, and frequency of coverage
* Timeliness of soil moisture information is as important as accuracy
* A program for coordinating and disseminating soil moisture information should be developed.

J. REFERENCES

Eagleson, P.S. 1970. Dynamic Hydrology. McGraw Hill, New York.

Idso, S.B., R.J. Reginato, R.D. Jackson, B.A. Kimball, and F.A. Nakayama. 1974. The three stages of drying of a field soil. Soil Sci. Soc. Amer. Proc. 38:831-837.

Jensen, M.E. (ed.). 1975. Consumptive use of water. Irrigation and Drainage Division, American Society of Civil Engineers. 215 p.

Kanemasu, E.T., L.R. Stone, and W.L. Powers. 1976. Evapotranspiration model tested for soybean and sorghum. Agron. J. 68:569-572.

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CHAPTER 4

SOIL MOISTURE ESTIMATION USING REFLECTED SOLAR AND EMITTED THERMAL INFRARED RADIATION

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A. INTRODUCTION

Classical methods of measuring soil moisture such as gravimetric sampling and the use of neutron moisture probes have been useful for cases where a point measurement is sufficient to approximate the water content of a small surrounding area. However, there is an increasing need for rapid and repetitive estimations of soil moisture over large areas. Remote sensing techniques potentially have the capability of meeting this need. We will examine the use of reflected-solar and emitted thermal-infrared radiation, measured remotely, to estimate soil moisture.

Physical, chemical, and electromagnetic properties of water are fundamentally different from those of dry soil materials. When water is added to soil, the properties of the resultant system change with the change in water content. In general, the amount of solar radiation reflected from the soil surface decreases with increasing water content. These changes in reflectance can be quantitatively related to the water content of the surface skin of soil. On the other hand, the amount of thermal radiation emitted from the surface is affected by the temperature of the surface which in turn is affected by the thermal properties of the soil/water system. Thus, a measure of emitted thermal radiation is indicative of the soil moisture within the layer of soil that influences surface soil temperature.

B. GENERAL OVERVIEW

For the purpose of presenting an overview of the vast amount of work that has been reported, the following discussion will be divided into the reflected and the emitted thermal IR, although a sharp separation is not always possible. Agrometeorological models that use remote sensing inputs are also discussed.

1. Reflectance Techniques

In the 0.4 to 2.5 μm range, the emitted component can be neglected at temperatures typical for the earth's surface, leaving the bidirectional reflectance as the only target parameter affecting the signal level measured. Atmospheric transmittance and path radiance effects can be computed (Selby and McClatchey, 1975; LaRocca, 1975). Consequently, variations in measured spectral radiance can be observed which are only due to changing bidirectional reflectance (provided that the incident radiance is uniform).

To determine soil water content from the above measurements, the effect of soil water and other variables on the bidirectional reflectance must be known. However, in only a limited number of studies has this factor been measured, and then usually for dry soils. Thus, the effect of moisture content and other soil variables is usually expressed in terms of the directional spectral reflectance, defined as bidirectional reflectance integrated over the upper hemisphere. The directional reflectance is a function of the direction of illumination only. Nevertheless, these measurements are useful since the spectral dependence established by means of directional measurements can be extrapolated for the bidirectional case (Maxwell, 1976).

This discussion of the reflection technique does not include effects of polarization. Although correlations between the index of polarization and soil moisture content have been reported (Stockhoff and Frost, 1971; Stockhoff et al., 1973), insufficient data are available for a thorough evaluation of this method. As pointed out by Stockhoff et al. (1973), however, this approach may warrant closer attention because of its lack of sensitivity to geometry and surface roughness.

Numerous measurements have shown that soil spectral reflectance increases between 0.25 μm and 0.80 or 1.00 μm (Condit, 1970; Von Minnus, 1967; Blanchard et al., 1974; LARS, 1970). When water is added, the spectral reflectance decreases in this wavelength range (Von Minnus, 1967; Condit, 1970). The spectral reflectance vs. soil moisture curves have similar shapes with a negative slope when plotted for individual wavelengths (Fig. 4-1). At high moisture contents, the reflectance values level off to a relatively constant value; in some studies (Von Minnus, 1967; Cihlar et al., 1971; Sewell and Allen, 1973; Blanchard et al., 1974), increases in reflectance were observed which can be attributed to specular reflection.

The absolute magnitudes of reflectance values vary considerably. A major parameter responsible for these differences is the spectral reflectance of a dry soil. Following laboratory measurements of 160 surface soil samples from various parts of the U.S., Condit (1970) divided the soils into three groups on the basis of the shapes of spectral reflectance curves: soils with reflectances which increased throughout the spectral range 0.32 to 1.00 μm; soils with spectral reflectance rising rapidly between about 0.35 and 0.75 μm but slowly beyond 0.75 μm; and soils with reflectances increasing slowly until 0.53 μm, fairly rapidly to 0.75 μm, and then leveling off or decreasing at about 0.82 μm before rising again to 1.00 μm (Fig. 4-2). These differences in spectral reflectances are due to chemical and mineralogical compositional variations (Krinov, 1953). As a rule, organic matter components (particularly humic and fluvic acids) decrease soil reflectance values throughout the visible spectrum; ferric oxide increases spectral reflectance between 0.53 and 0.58 μm, especially if present as coating on soil particles; and quartz, carbonates, and some secondary soil minerals increase reflectances throughout the visible spectrum (Obukhov and Orlov, 1964; Steiner and Gutterman, 1966).

Texture and structure affect soil reflectance. After examining 22 southern Ontario soils ranging from sand to silty clay, Cihlar et al. (1971) concluded that at a given moisture content, the soil reflectance (expressed as the total reflectance in the 0.36 to 0.78 μm region) increased with increasing proportion of fine particles (Fig. 4-3); the relationship was sensitive to small changes in soil texture. Furthermore, the constant low reflectance was reached sooner by the coarser soils. Myers and Allen (1968) reported that fine-textured soils can have structures that give them the characteristics of aggregate coarser than sand. Structureless soils reflect as much as 15 to 20 percent more solar radiation than soils with well-defined structures (Myers, et al., 1975).

According to Obukhov and Orlov (1964), the moisture content at which reflectance becomes constant corresponds to the full capillary moisture capacity. Similar conclusions were reached by Janza et al. (1975) who also discussed the effect of various soil components on spectral reflectance.

Surface roughness is an important modifier of the spectral reflectance. It contributes to shading which results in a decreased reflectance value; for example, Coulson and Reynolds (1971) found that the directional reflectance of a dry disked Yolo loam (clod size from a few millimeters to 10 cm) was almost identical to that of a Yolo loam with a completely wet and very flat surface (Fig. 4-4). This effect is probably enhanced by the multiple reflections which increase for rough surfaces, thereby decreasing reflectance (Orlov, 1966).

a. Bare Soils

In a controlled ground experiment, Idso et al. (1975c) measured the directional reflectance (0.3 to 2.5 μm band) and water content for a smooth Avondale loam at various depth intervals from 0.0 to 10 cm. After correcting reflectance measurements for solar zenith angle effects, they found a linear relationship with the soil moisture over the range 0.0 to 0.18 cm^3/cm^3 in the 0.0 to 0.2 cm layer. Similar relationships were also well defined for deeper layers but these were evidently due to the close correlation between moisture contents at the surface and at various soil depths (measurements were carried out during four drying cycles following an irrigation with 10 cm of water). Reginato et al. (1977) extended this study to airborne data collected over smooth and rough Avondale loam plots at different moisture contents. They confirmed the relationship between albedo and soil water content established by

Idso et al. (1975c). Consistent with previous laboratory results, they found that ratios of amounts of radiation reflected in various bands were not related to soil water content in the wavelength range 0.45 to 1.03 μm.

Moore et al. (1975a) correlated Skylab S-192 multispectral scanner measurements (0.56 to 0.61, 0.68 to 0.76, 0.78 to 0.88, 1.55 to 1.75, and 2.10 to 2.35 μm) with soil moisture content of three different layers (0 to 2, 2 to 10, and 10 to 30 cm) for 13 fields. The highest correlation coefficient which was highly significant (-0.672) was obtained for the 2.10 to 2.35 μm band and depth 0 to 2 cm. Two of the fallow fields (wet and dry, respectively) could not be statistically separated at wavelengths shorter than 1.55 μm. Wavelengths greater than 2.1 μm were required to reliably spectrally distinguish between wet and dry bare surfaces in the study area.

According to Idso et al. (1974), the three stages of drying (energy-limited, transitional, and soil-limited) can be determined from directional reflectance measurements; furthermore, the transitional stage evaporation rate can be computed by using directional reflectance as one of the input parameters along with potential evaporation, wet and dry soil reflectance values, and a soil type dependent coefficient (Jackson et al., 1976).

b. Vegetated Soils

In the presence of a vegetation cover, the total reflected radiation consists of the reflection by the soil modified by the plant canopy, and of the canopy-reflected component. Because of the high spatial and temporal variability and attendant difficulties inherent in recovering the soil spectral reflectance from the composite reflectance measurements, it appears unlikely that the same principle as for bare soils (i.e., reflectance decrease following addition of water) can be applied. It may be possible, however, to use plants as indicators of soil water content. Werner et al. (1971) investigated the relationship between film densities and the available water content in the root zone for sorghum. They found that the 0.59 to 0.70 μm band yielded the highest correlations with moisture.

Another approach was used by Heilman et al. (1977) to determine soil water content of winter wheat fields in five states of the U.S. They employed an evapotranspiration model (with solar radiation, maximum and minimum air temperatures, precipitation, and leaf area index determined from Landsat data as inputs) to monitor the amount of water in the top 150 cm of soil. The soil moisture estimates compared favorably with the traditional Crop Moisture Index, and in addition, could be interpreted in terms of yield through the evapotranspiration model.

c. Summary

The results discussed above show that the soil spectral reflectance vs. water content relationship depends on several other variables such as spectral reflectance of the soil when dry, surface roughness, geometry of illumination, organic matter, and soil texture. Several of these variables are time invariant or could be so made by a proper choice of remote sensing mission parameters. Others, particularly surface roughness and surface cover, vary with time. Considering these effects and the fact that the reflected radiation varies with many factors in addition to soil moisture, direct measure of soil moisture is complicated. However, comparison of temporal landscape reflectances over short time periods, such as one day where all other variables are relatively constant, may indicate differences in soil moisture for bare soil. For soils with vegetation, 0 to 100% cover, the most effective use of reflectance data is to provide input into agrometeorological models for soil moisture budgets.

2. Thermal Infrared (Emission) Technique

The thermal infrared technique of soil water content estimation of bare soils is based on the relationship between surface soil temperature and near-surface soil moisture (Cihlar, 1976). The soil temperature for a bare surface results from interactions among four energy fluxes at the soil-air interface, namely net radiation R, sensible heat H, latent heat LE, and soil heat flux G; according to the energy balance equation, their sum is equal to zero. The magnitude of each flux depends on several parameters. Net radiation consists of the surface-absorbed shortwave solar radiation and longwave atmospheric counter-radiation, minus thermal infrared emission by the surface. Sensible heat is directly proportional to the vertical temperature gradient and a transfer coefficient, the latter being a function of surface roughness and wind speed. Latent heat flux represents the loss of heat due to evaporation from the soil; it depends on water transmitting properties, surface roughness, wind speed, and the vertical humidity gradient. Soil heat flux (G) can be expressed analytically for a homogenous semi-infinite soil, the surface of which is heated in a periodical manner, and time t (Sellers, 1965):

$$G(t) = 1/2\,(T_{s,max} - T_{s,min})\,\beta\omega^{1/2} \sin(\omega t + \pi/4),$$

where: $$\beta = (\rho\, C\, \lambda)^{1/2},$$

$T_{s,max}$ = maximum value of the surface temperature; [4-1]

$T_{s,min}$ = minimum value of the surface temperature;

t = time

C = soil heat capacity, cal g^{-1} C^{-1};

β = soil thermal inertia, cal cm^{-2} C^{-1} $sec^{-1/2}$;

ω = angular frequency, rad sec^{-1};

λ = soil thermal conductivity, cal cm^{-1} C^{-1} sec^{-1};

ρ = soil bulk density, g cm^{-3}

Surface soil temperature may be computed if the above fluxes or factors determining them are known. Models have been developed (Outcalt, 1972; Kahle, 1977; Rosema, 1975) which can be used to predict diurnal surface temperature changes for a given set of astronomical, site, and meteorological parameters (some of them as a function of time). Conversely, apparent thermal inertia may be determined from surface temperature measurements (Price, 1977); this step is important for soil moisture estimation from remotely obtained data.

As the soil water content increases, the amplitude of the diurnal surface temperature wave becomes smaller; i.e. ($T_{s,max}$ - $T_{s,min}$) decreases. This inverse relationship has been verified by Idso et al. (1975e) in a series of experiments (Fig. 4-5). Although the experiments were conducted at different times, the seasonal effects could not be detected and were probably overshadowed by other parameters such as varying wind speed. The inverse relationship was linear for ($T_{s,max}$ - $T_{s,min}$) or for ($T_{s,max}$ - $T_{a,max}$) (where $T_{a,max}$ is air temperature measured at the time of $T_{s,max}$) when soil moisture was measured for 0 to 2 or 0 to 4 cm depths. Idso et al. (1976) found that the day-to-day effect of air temperature on the above relationship could be reduced using the diurnal air temperature differential ($T_{a,max}$ - $T_{a,min}$) as a normalizing factor.

The modulating effect of soil water on the surface temperature is due to latent heat and thermal inertia. Since approximately 590 calories are needed to evaporate 1 gram of water, less energy is available for warming the soil when the evaporation rate is high. Soil thermal inertia increases with increasing water content (Fig. 4-6), thus increasing heat conduction away from the surface. Note that both factors act in the direction of the ($T_{s,max}$ - $T_{s,min}$) decrease with increasing moisture content.

Soil thermal inertia is a function of the thermal conductivity, heat capacity, and bulk density, which are in turn related to the physical, chemical, and mineralogical composition of the soil. Watson (1975) has shown on the basis of experimental data that the thermal inertia of a dry soil is directly proportional to bulk density. At higher water contents, energy relations of soil water affect not only thermal conductivity but also the extent to which water is available at the evaporation sites. Consequently, evaporation rate, the magnitude of latent heat loss, and ($T_{s,max}$ - $T_{s,min}$) should vary between soil types at identical moisture contents. Idso et al. (1975e) confirmed experimentally the soil type dependence of the ($T_{s,max}$ - $T_{s,min}$) vs. volumetric water content relationship. They also found that if soil water was expressed in units of pressure potential, this dependence was minimal. (Fig. 4-7).

When a soil is covered with vegetation, the relationship between the received signal and T_s is considerably modified by the canopy which acts as an attenuator of the soil emission and adds its own emission component. Secondly, the T_s vs. soil moisture dependence changes because the energy fluxes are affected by the presence of plants. Since these various interactions are very complex, it would be difficult to apply the same principles for soil moisture detection under plant canopies as were used for bare soils. However, a potential for soil moisture detection under canopies by thermal infrared remote sensing still exists and is based on the increase in plant temperature caused by reduced transpiration rate resulting from soil water deficiency. This relationship has been reported by Wiegand and Namken (1966), Wiegand et al. (1968), Thomas and Wiegand (1970), Nixon et al. (1973), Millard et al. (1977a), and Idso and Ehrler (1976).

a. Bare Soils

Reginato et al. (1976) conducted an experiment designed to confirm and extend results shown in Fig. 4-5. They measured $T_{s,max}$ and $T_{s,min}$ by three methods (thermocouples, hand-held radiation thermometer, airborne thermal infrared scanner) for smooth and rough (roughness elements 0 to 10 cm) Avondale loam plots, as well as gravimetric water contents at different depths and times of day. The results (Fig. 4-8) confirmed the inverse $(T_{s,max} - T_{s,min})$ or $(T_{s,max} - T_{a,max})$ vs. moisture relationships at water contents below field capacity, i.e., for the transitional and soil-limited evaporation stages. For moisture contents between saturation and field capacity, the temperature differentials remained approximately constant. Since thermal inertia decreases with decreasing moisture content (Fig. 4-6), the sudden change in the temperature differentials near field capacity points to the importance of latent heat as a mechanism for modifying surface temperatures measured by the three methods (remote measurements were corrected for emissivity) as well as a reasonable time invariance of the relationships of moisture vs. temperature differentials (full dots in Fig. 4-8a, c represent measurements from previous experiments). Similarity between results for smooth and rough plots (Fig. 4-8a, c vs. b, d) is somewhat surprising due to the role roughness plays in surface energy exchange; additional work is needed to determine whether differences in other parameters such as soil bulk density (not included in Fig. 4-8) are involved.

Idso et al. (1975b) have shown that the two temperature differentials can also be used to estimate daily evaporation from bare wet and drying soils. Application of this method requires a knowledge of daily solar radiation, maximum and minimum air temperatures, moist surface directional reflectance, and maximum and minimum surface temperatures. If potential evaporation values are available, actual evaporation can be determined from the temperature differentials alone (Idso et al., 1975d; Reginato et al., 1976).

LeSchack et al. (1975) measured moisture content 10 cm below the surface and thermal infrared emission with an airborne scanner over bare and vegetated agricultural fields. Their analysis indicated a positive linear relationship between maximum surface temperature and gravimetric water content. The reason for the contradiction (compared to theory and other results) is not obvious; it might be related to the profile distribution of soil moisture at the sampled sites or the narrow range of temperatures observed (3° C). Bartholic et al. (1972) used an airborne scanner to measure temperatures of bare and cotton fields which were under different moisture treatments. They obtained temperatures ranging from 29° C for well-watered cotton to 37° C for a dry cotton plot. Similarly, bare soil temperature was lowest for the wettest field and increased as moisture content decreased. Sumayao et al. (1977) found that for sorghum on warm days (air temperature greater than 33° C) the air was warmer than upper canopy leaves when the available profile soil moisture was greater than 35 percent of the maximum available soil moisture; below 35 percent of maximum available soil moisture leaves were warmer than air.

During 1976, an experiment was conducted by the Canada Centre for Remote Sensing in southern Alberta to test the validity of surface temperature vs. soil moisture relationships in fallow fields. Preliminary results indicate that the relationship between surface temperature and soil moisture in the top 2 to 4 cm holds for partly mulched (straw) fields, although in a somewhat degraded form. Soil moisture determination may be improved by employing visible reflectance measurements.

Moore et al. (1975) studied the usefulness of Skylab S-192 thermal infrared measurements for evapotranspiration and soil moisture mapping. They found that the 10.2 to 12.5 μm band measurements correlated significantly with moisture contents in 0 to 2, 2 to 10, and 10 to 30 cm layers (correlation coefficients -0.64, -0.60, and 0.73, respectively); the data represented both fallow and alfalfa (10 to 89% green cover) fields. Thermal infrared measurements could be used to separate wet and dry fields but not various cover types; a reflective band would be suitable for the latter purpose.

b. Vegetated Soils

For agricultural purposes, one is interested in soil moisture primarily because of its effect on plant growth. Since canopy temperature is more directly indicative of plant water stress, it may not be necessary to know the soil moisture content if direct relationships could be established between canopy temperature and other parameters of interest such as yield, need for irrigation, etc. However, detection of increases in canopy temperature may be too late for indicating irrigation needs since yield may already be reduced. When viewing a cropped surface, if the vegetation is reflecting the soil moisture status, a potential exists for monitoring effective soil moisture over the rooting depths of the particular crop. Following this argument, Jackson et al. (1977) established that a running sum of daily values called "Stress Degree Days" (SDD) can potentially be used for irrigation scheduling. Millard et al. (1977b) confirmed feasibility of this approach for fully grown wheat on the basis of airborne data. Similarly, stress degree days have been successfully correlated with the yield of wheat (Idso et al., 1977).

c. Summary

The above discussion indicates that the thermal infrared techniques of soil water content estimation hold considerable promise. The main task appears to be a comprehensive testing of the concepts developed in controlled ground experiments over various climatic regimes by means of aircraft and satellite measurements. These tests should yield information on the operational feasibility of the proposed concepts. In addition, limitation of these concepts should be ascertained (for example, practically all work so far has been site-specific under clear-sky conditions) to provide the basis for the choice of an optimum remote sensing method.

d. Atmospheric Effects on Thermal Measurement

Assuming cloud-free conditions a satellite radiometer may obtain an approximate value of surface temperature through the measurement of the energy emitted by the surface. Such measurements are usually carried out in the atmospheric spectral "window" between 10 and 13 μm. Thermal emission measurements may also be carried out at night in another "window" at approximately 3.7 μm. Inference of surface temperature is not feasible at this wavelength during daylight hours because reflected sunlight adds to the signal, producing too high an estimate of surface temperature.

When accurate values of surface temperature are required, radiometric measurements in the 10 to 13 μm spectral interval must be corrected for the effect of atmospheric moisture. This moisture, which is generally concentrated in the lowest 1 to 3 kilometers of the atmosphere, absorbs part of the earth's emitted radiation, and emits radiation corresponding to its own temperature. Solution of the pertinent differential equation may be obtained with a digital computer, given the mixing ratio and temperature as a function of height. However, the appropriate value for the spectral absorption coefficient is not very accurately known because its numerical value is so small that it is difficult to measure in the laboratory. Accepted values show that this coefficient is dependent on the mixing ratio, i.e., the atmospheric transmission is proportional to the square of the mixing ratio (Bignell, 1970).

For the radiative transfer calculation the temperature and humidity of the atmosphere may be obtained from meteorological soundings, or they may be estimated by extrapolation to higher levels of near surface measurements. In either case spatial interpolation is needed to produce atmospheric correction values on the grid spacing at which soil moisture values are to be derived using remote thermal measurements. A minimum requirement is for estimates of the atmospheric state at the time of satellite observations on the meteorological synoptic scale (e.g. 1000 km). It is possible that smaller scale (mesoscale) atmospheric variation may have a variable effect on transmission of radiation through the atmosphere, thereby generating a requirement for a relatively dense set of meteorological observations to support remote sensing of soil moisture at intervals of 10 to 100 kilometers.

The subject is still an important field of research since a detailed study of the potential accuracy of remote sensing, including the effect of variable surface emissivity and the adequacy of calibration methods (Williamson, 1977) has not been carried out to date. However, the uncertainties are small enough (temperature errors of the order of a few degrees centigrade) to permit use of remote sensing for soil moisture studies.

One feature of the atmospheric correction should be noted - the temperature correction is not a constant for a particular atmospheric state. The correction to satellite observations will be larger for very hot surfaces than for cool surfaces. If the surface is cooler than the weighted mean temperature of atmospheric water vapor, i.e., a meteorological inversion, the correction changes sign. In this case the remote measurement indicates a temperature higher than the actual surface temperature. It follows that care must be exercised in the use of remote thermal measurements for the estimation of soil moisture.

3. Agrometeorological Models Using Remote Sensing Inputs

For many agricultural applications daily estimates of soil moisture are required (crop management practices--irrigation scheduling, planting date, herbicide and pesticide applications; yield predictions; growth and phenology modeling). Many models that estimate soil moisture are not applicable to large regions because the required meteorological or cropping data are not available (Ritchie, 1972; Saxton et al., 1974).

Central to most models is the estimate of evapotranspiration (ET) which is composed of evaporation and transpiration. Unfortunately, evaporation from the soil surface and transpiration from the plant surfaces are physically two different processes; therefore, they must be estimated separately and summed. Usually over a typical growing season, transpiration will comprise about 60 to 80% of the total ET; therefore, an estimate of the area of the evaporating surface (green leaf area) is important. Because the green leaf area is constantly changing (due to growth, senescence, drought, disease, insects, fertility, hail, etc.) an evapotranspiration model must mimick the effective green leaf area, preferably day by day, or include it as a daily external input.

Shown in Fig. 4-9 is a flow diagram of a soil moisture model that incorporates leaf area index (ratio of green leaf area to soil area) with minimum meteorological data (temperature, solar radiation and precipitation). Leaf area index (LAI) is estimated from Landsat data. Assuming adequate coverage, one can extrapolate between overpasses to obtain the daily LAI values.

In the model, the energy-limited evapotranspiration occurring from a well-watered surface under non-advective conditions is estimated by

$$ETmax = \alpha[s/(s+\gamma)]Rn \qquad [4\text{-}2]$$

where α is a constant for a particular crop and climatic situation (α=1.35 for wheat and corn in Kansas); γ is the psychrometric constant; s is the slope of the saturation vapor pressure curve at a mean temperature; and Rn is the 24 hour net radiation. Net radiation is estimated from solar radiation (Rs) by

$$Rn = a + bRs \qquad [4\text{-}3]$$

where a and b are constants.

Evaporation from the soil surface can be estimated by a method suggested by Ritchie (1972) where the constant rate stage (E_1) is limited by the energy supplied and is given by

$$E_1 = \tau\ ETmax/\alpha \qquad [4\text{-}4]$$

where τ = exp β(LAI); and β is a crop dependent constant (β = -.398 for corn; β = -.737 for wheat). The second stage or the falling rate stage of evaporation (E_2) is given by

$$E_2 = ct^{1/2} - c(t-1)^{1/2} \qquad [4\text{-}5]$$

where c is a soil constant and t is the day into the second stage. The second stage begins after E_1 has summed to a threshold value of U.

Transpiration is estimated by equations of the form presented by Tanney and Jury (1976) and Kanemasu et al. (1976). When the available moisture content in the root zone is greater than 30% of maximum available water, the relations

$$T = \alpha_v(1-\tau)[s/(s+\gamma)]Rn \qquad \text{crop cover} \leq 50\% \qquad [4\text{-}6]$$

and

$$T = (\alpha-\tau)[s/s+\gamma)]Rn \qquad \text{crop cover} > 50\% \qquad [4\text{-}7]$$

are used. In the relations the term α_v is 1.56 for wheat and 1.74 for corn. When the available moisture content is less than 30%, the transpiration rate is linearly decreased to zero at zero available moisture.

An advective contribution (A) during very warm days and well-watered conditions is estimated by

$$A = 0.1\ (Tmax - Tc)T \qquad Tc<Tmax<38^{o}C \qquad [4\text{-}8]$$

where Tc is a crop dependent temperature (Tc = 23°C for winter wheat, Tc = 33°C for corn); and Tmax is daily maximum temperature.

The total daily evapotranspiration (ET) is given by

$$ET = E + T + A. \qquad [4\text{-}9]$$

Changes in soil moisture (ΔS) can be estimated from a water balance given by

$$\Delta S = P - ET - R - D \qquad [4\text{-}10]$$

where P is the precipitation, R is the runoff, and D is the deep percolation. Provided the RHS terms are known or can be estimated, soil moisture can be estimated on a daily basis if an initial soil moisture content is known. Kanemasu et al. (1977) estimates R and D from P and soil moisture.

C. SOME SPECIFIC CASES

1. Reflected Solar Detection of Shallow Water Tables

Shallow or "perched" water tables exhibit both direct and surrogate indications of their presence in the visible and reflective infrared regions. The reflectance of most soils is inversely related to soil moisture (Bowers and Hanks, 1965). This relationship, however, does not consistently apply over extreme conditions of either low or high soil moisture and is dependent upon soil type. Using sequential Landsat imagery directly after precipitation appears indicative of percolation/dry off rates; drainage problem areas can be distinguished because of slower rates of drying (Jet Propulsion Laboratory, 1976).

Vegetation condition (damage) is also useful for detecting areas affected by drainage problems (Moore, 1974; Gates, 1966). This approach does not require precipitation and is therefore easier to implement. A comprehensive comparative evaluation between the two approaches has not been completed. In general however, they seem broadly comparable.

For monitoring purposes either approach can be implemented using conventional visual interpretation. Image enhancement techniques could be useful if implemented in a consistent manner (Lidster et al., 1975). Due to the number of variables involved (notably topography, soil type, vegetative type and stage, and atmospheric conditions) future automation of this procedure will be difficult (Moore, 1974; Estes et al., 1978). An informed interpreter will most likely always be involved as an integral part of the monitoring program.

2. Drought Assessment Using Reflected Solar Radiation

Thompson (1976a) compared spectral monitoring of crop moisture deficiencies using Landsat digital and image data with the meteorological Crop Moisture Index (CMI) of Palmer (1968), and quantified the subjective judgments of image interpreters in the Large Area Crop Inventory Experiment (LACIE) about drought conditions in a multistate winter wheat producing area. This development is based on the fact that color infrared photographs and Landsat color composite images register differences in green vegetation density and vigor because of the high near infrared (0.75 to 1.35 μm) reflectance of green vegetation compared with the soil background or water. The computer compatible tapes (CCT) from Landsat bands 6 and 7 (.7 to 1.1 μm) express the information digitally. Since soil water deficit reduces plant growth, drought can be detected from the appearance of the vegetation relative to its appearance at the same time of year under nondrought conditions.

Landsat digital tapes were obtained for portions of five Great Plains states during the "normal" 1975 winter wheat growing season and the droughty 1976 growing season. A Green Index (GIN) was calculated, using the formulas of Kauth and Thomas (1976), for wheat fields of the study area of the two seasons. The GIN was compared with the weekly CMI published by NOAA and was studied in relation to gauged rainfall for the study area. Thompson (1976a) found that Landsat data provided a more accurate estimate of area affected than does CMI and that Landsat spectral data can delineate precipitation patterns and effectiveness for crop growth during the growing season. The approach has also been applied to Crop Reporting Districts (CRD) of South Dakota by Thompson (1976b) and Thompson and Wehmanen (1977).

3. Plant Water Content by Visible to Middle Infrared Reflectance Measurements

In the wavelength interval 1.35 to 2.5 μm, it is the water content of plants that is primarily responsible for their optical behavior. In addition, in the .75 to 1.30 μm interval, the amount and distribution of highly hydrated green biomass can be revealed by reflectance measurements. Thomas et al. (1971) and Carlson et al. (1971) investigated the reflectance of cotton, and of corn, sorghum, and soybean, respectively, in the laboratory over the 0.5 to 2.5 μm wavelength interval as a function of relative water content of the leaves. They found that the relative water content or relative turgidity of plant leaves was highly correlated with two strong water absorption bands, 1.45 and 1.95 μm. Tucker (1976) measured reflectance of natural blue grama stands over the wavelength interval 0.35 to 1.00 μm and related them to green biomass and leaf water content (i.e., weight difference between fresh and oven-dried leaves). He found three spectral regions of strong statistical significance-- .35 to .50, .63 to .69, and .74 to 1.00 μm. The significance in the ultraviolet-blue region is related to the carotenoid and chlorophyll pigment content of live vegetation, in the red region to chlorophyll absorption, and in the reflective infrared to leaf structure of live vegetation.

Reflectance differences in other than the reflective infrared are small. Thus other sources of variability among fields and plants within them (age differences among leaves and water stresses under which they developed) would obscure the relationships.

4. Watershed Curve Numbers

The Soil Conservation Service (SCS) hydrologic model relates runoff to watershed curve numbers that are a function of the distributions of land covers and soil types. The soil types are associated with infiltration rates, permeabilities, and water holding capacities. If the soils and their vegetative covers could be grouped or delineated by remote sensing techniques, runoff estimates would be improved. Blanchard (1975, 1978) attempted to modify the existing SCS model by estimating runoff curve numbers directly by reflectance measurements made by the Landsat multispectral scanner. He separated watersheds in Oklahoma into spectrally similar parts in the Landsat MSS data, and related linear combinations of the spectral data to traditionally established curve numbers. In a second study over test sites in Texas and Arizona, data were selected for the dormant season (Oct. to Mar.), dry periods (indicated by antecedent precipitation index, API), and cloud-free scenes. In Oklahoma, Blanchard found that the digital data for the red visible minus the green visible light band (band 5 - band 4) and [(band 5 + band 6) - (band 4 + band 7)] correlated with the curve number. He could not find similar relationships for the Texas or Arizona watersheds, however, and concluded that where vegetation grows throughout the year, wet surface conditions prevail, or if the watersheds are timbered the Landsat spectral data will be difficult to relate to curve number.

The Texas and Arizona watersheds either could not be characterized by the Landsat wavelengths, or the dominant parameters in their runoff behavior (slope, impermeable areas, etc.) were inadequately known and weighted. Thermal and microwave data may help characterize such watersheds, but other ways to examine the spectral data need to be examined (Blanchard, 1977). Ragan (1977) has recently reviewed many instances of success in augmenting other data with remotely sensed inputs and feels that the most progress will come not by modifying existing models, but by evolution of new models that take advantage of remote sensing capabilities. Land use and vegetative cover are two inputs to hydrologic modeling that appear to be operationally measured from Landsat data (Richardson and Wiegand, 1977).

5. Detection of Plant Water Stress Due to Salinity

Saline soils are a world-wide problem on irrigated and non-irrigated arid and semi-arid land. The presence of water soluble salts in the root zone causes an osmotic suction which reduces the availability of water to plants. Plants growing in saline soil exhibit marked symptoms of moisture stress, and growth is retarded. Salinity effects on plant growth and hydration, water availability, and transpiration rate affect the equilibrium leaf and canopy temperature (Myers et al., 1970). Myers et al. (1966) and Thomas and Wiegand (1970) measured cotton plant leaf temperatures with a Stoll-Hardy thermal radiometer in fields that were characterized for soil salinity, plant growth, and leaf turgidity. Incident solar radiation and air temperature were measured simultaneously with the leaf temperature measurements. Leaf temperatures were related to various degrees of salinity and the separate effects of matric and osmotic suctions on plant growth, relative turgidity, and temperature of cotton leaves were determined under field conditions. Soil salinity could be predicted with reasonable accuracy from the leaf-air temperature difference ($r = .84$). Simultaneously obtained photography and thermal images will together display the growth and water stress patterns necessary to diagnose extent and severity of soil salinity during the crop season. Digital data in the reflective infrared (.75 to 1.30 μm) and thermal (8 to 14 μm) bands can quantify the data that images record and display. Biological stresses such as nematode damage to roots will also restrict water uptake and cause effects similar to those caused by salinity. Under conditions of both biological stress and salinity, auxiliary measurements need to be made to identify the cause of the stress.

6. Thermal Inertia Approach to Soil Moisture Estimation

The thermal inertia technique derives estimates of soil moisture from measurements of surface temperature at times near the maximum and the minimum of the diurnal temperature cycle. The method relates differences of soil surface temperature to soil moisture content. The principle is one of common experience; dry soils heat up more at midday than do wet soils. Thus the amplitude of the surface temperature variation is (roughly) inversely proportional to the surface moisture content.

Measurement of temperature differences minimizes several problems associated with remote sensing of surface temperature: absolute calibration of the observing instrument, the correction for a non-unit value of surface emissivity, and the influence of atmospheric effects, principally water vapor. To some degree these effects cancel out when a temperature difference is formed.

The variation of surface temperature of a soil depends on the moisture content in three ways. This dependence may be broken down to the level of elementary material properties.

(1) Thermal conduction transfers as heat some of the solar energy that strikes the surface into a soil, thereby limiting the excursions of surface temperature about the daily mean value. An increasing thermal conductivity (λ) means greater depth of penetration of the diurnal temperature wave over certain ranges of soil moisture, and a decreasing day-night surface temperature range. For soils λ increases as soil moisture increases, but with moisture the effect of heat capacity overrides diurnal fluctuations resulting in a damping of the fluctuations. Therefore, a thermal diffusivity (or rates of conductivity and heat capacity) term is the controlling influence of soil properties affecting soil temperatures.

(2) The heat capacity (energy input per unit mass per degree Centigrade temperature change) determines the amount of energy needed to raise the temperature of a given mass of material. A substance with a high heat capacity will have a relatively smaller temperature variation due to a given input of energy than one with a low heat capacity. Heat capacity (C) increases with soil moisture, principally due to the high heat capacity of water.

(3) The density (ρ) affects the surface temperature variation through its effect on volumetric heat capacity. The effective density of a soil increases as its moisture content increases.

The amount of energy which is stored in the near surface layer during the day, and released at night, is related to the product of the three terms, i.e. $\rho C \lambda$. Fortunately, all three quantities change in the same way with soil moisture. The result is that for a given solar energy input, a dry soil shows a greater day-night temperature difference (ΔT) than a moist soil. Neglecting evaporation, ΔT is inversely proportional to the thermal inertia $(\rho C \lambda)^{1/2}$. Thus, measurement of ΔT permits the inference of soil moisture, given that the dependence of thermal inertia on water content has been established. The magnitude of the thermal inertia depends somewhat on soil type and texture (Idso et al., 1975e; Idso, et al., 1976).

A complicating factor is the effect of surface evaporation in reducing net energy input from the sun. Evaporation complements the other effects of water in soil by reducing the amplitude of the surface diurnal temperature cycle. As a result the day-night temperature difference is an indicator of some combination of soil moisture and surface evaporation. Current research efforts are directed toward clarifying the relationship between soil moisture, evaporation, and the variation of surface temperature (Deardorf, 1977). A NASA program, the Heat Capacity Mapping Mission, will test the feasibility of using remote observations to infer soil moisture. A special data product, "apparent thermal inertia" will be generated as a possible indicator of the conditions of the surface layers of soil. This quantity is defined as (constant) x (1.0 - albedo)/(day temperature - night temperature), where the albedo and temperature measurements will be obtained by the satellite radiometer. Satellite overpass will occur at 2:30 a.m. and 1:30 p.m. local time. Some theoretical justification has been given for this formula (Price, 1977). The satellite program will attempt to establish a quantitative capability - i.e., to estimate moisture content at each $(500\ m)^2$ area under satellite observation.

D. STATE OF THE ART

Remote sensing of soil moisture using reflectance and thermal infrared techniques can achieve qualitative results (Blanchard et al., 1974). Drought and flooded areas can be delineated by their reflectance properties. Shallow water tables can be located with thermal IR, etc. However, the degree to which soil moisture can be quantitatively measured using these techniques is a point of disagreement among researchers in this field. The opinions of the authors of this report are rather divergent concerning this point.

The great advantage of a remote sensing technique for measuring soil moisture is that large areas can be rapidly surveyed. This advantage has the serious handicap of calibration. Essentially all classical techniques of measuring soil moisture rely on point measurements. The notorious non-homogeneity of soils complicated by the equally notorious non-homogeneity of water content within a soil make adequate comparison of the two techniques extremely difficult. More experiments need to be done to adequately calibrate remote sensing techniques. Also, operational evaluations of certain promising techniques that use remotely sensed data are currently limited by slow turn around and dissemination of data.

For bare soils, reflectance measurements are affected only by the surface particles and the water surrounding them (Idso et al., 1975a). Thus, the reflectance technique will essentially give only a yes/no answer, that is, whether the surface is wet or dry. As long as the water films surrounding the particles are connected to those beneath, water will move to the surface particle and evaporate with the reflectance remaining essentially constant. When the water content decreases to the point that the films are so thin that water cannot move to the surface particle at a sufficient rate to sustain the evaporative loss, the surface particle will rapidly dry and the reflectance will increase by about a factor of two. This point is not reached by all surface particles at the same time. Thus, we have a transition period for a field where the reflectance increases as the surface dries. By following the reflectance changes with time, a qualitative estimation of the moisture status of a soil can be made.

For vegetated soils, reflectance measurements can give estimates of plant cover, i.e. leaf area index, biomass, percent ground cover, etc. They can also indicate when plants are stressed. In some plant species the stress (water or biological) may cause damage before being detected by reflectance measurements.

The thermal IR technique has the capability of measuring soil moisture of the near-surface layers. The thermal inertia approach has a sound theoretical basis but is complicated by heat transfer as a result of evaporation, and by environmental conditions. For example, wind, water vapor content of the air, and air temperature can affect the measurement. Since a measure of the day temperature maximum and the night minimum is required, various environmental factors can change during the time between measurements. A simple normalization procedure proposed by Idso et al. (1976) that utilizes the air temperature difference will compensate for some, but not all, of the effects of the various factors.

The thermal IR has proven useful in detecting stress in vegetation. Although it has not been conclusively demonstrated, it appears that stress can be detected by thermal IR before significant reflectance changes occur. When a plant is actively transpiring the evaporation of water cools the leaves. As transpiration decreases (due to water or biological stresses) less water is evaporated and the plant temperature increases in relation to a non-stressed plant. If transpiration were linearly related to available soil moisture (which it definitely is not), the temperature change could be used as an index of soil moisture. On the other extreme, if transpiration remained constant over the entire range of available moisture, the thermal IR technique would be a yes/no - wet/dry indicator. The true relation lies between the extremes and is dependent on the type of plant. There is general agreement that transpiration is little affected as available soil moisture decreases from field capacity to some point. The disagreement is at what soil water content the transpiration rate begins to decrease and what is the shape of the relationship from that point on to wilting. More research will be required before the full usefulness of the thermal IR in vegetated soils can be realized.

Agrometeorological models are available that can be used to predict soil moisture and soil moisture profiles. The assessment of model accuracy is not unanimous among researchers; however, they have proven useful for many practical applications. A great advantage is that the models will work when weather conditions prohibit remote sensing measurements. The use of an agrometeorological model as a day to day predictor, supplemented by remote sensing inputs, has perhaps the greatest potential for quantitatively estimating soil moisture at the present time.

E. KEY-POINT SUMMARY

* Current reflected-solar and thermal-infrared techniques are most successful for bare soil and for complete canopy cover, and are least successful for intermediate canopy cover.
* A relationship exists between near-surface soil moisture and reflected-solar and emitted-thermal infrared radiation.
* Agrometeorological models supplemented by remote sensing inputs presently have the greatest potential for predicting soil moisture and soil moisture profile on a daily basis.
* More multispectral (visible and near infrared, thermal, microwave) modeling research is required.
* Multiple-sensor studies (including meteorological satellites) should be conducted at several geographically dissimilar sites.
* The capability for rapid turn-around and dissemination of data must be developed for testing in an operational mode.

F. BIBLIOGRAPHY

Bartholic, J.F., L.N. Namken, and C.L. Wiegand. 1972. Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water stress. Agronomy Journal 64:603-608.

Bignell, K.J. 1970
Quart. Journal Royal Met. Soc. 96:390-403.

Blanchard, B.J. 1975. Remote sensing techniques for prediction of watershed runoff, paper W-15, NASA Earth Resources Survey Sympos. Houston, TX.

Blanchard, B.J. 1978. Spectral measurement of watershed coefficients in the Southern Great Plains. Remote Sensing Center, Texas A&M Univ., Rpt. RSC 3273 (preprint)

Blanchard, B.J. 1977. Demonstration to characterize watershed runoff potential by microwave techniques. Remote Sensing Center, Texas A&M Univ., Rpt. RSC-3345.

Blanchard, M.B., R. Greeley, and R. Goettelman. 1974. Use of visible, near-infrared, and thermal infrared remote sensing to study soil moisture. NASA Technical Memorandum TM X-62, 343. 4p.

Blanchard, M.B. and R. Greeley and R. Goettleman. 1974. "Use of visible, Near Infrared and Thermal Infrared Remote Sensing to Study Soil Moisture". Proceedings 9th International Symposium on Remote Sensing of Environment. Environmental Research Institute of Michigan, Ann Arbor.

Bower, S.A. and R.J. Hanks. 1965. Reflection of radiant energy from soil. Soil Science, Vol. 100.

Carlson, R.E., D.N. Yarger, and R.H. Shaw. 1971. Factors affecting the spectral properties of leaves with special emphasis on leaf water status. Agronomy Journal 63:486-489.

Cihlar, J. 1976. Soil moisture determination by thermal infrared remote sensing. Proceedings of the Workshop on Remote Sensing of Soil Moisture and Groundwater, 8-10 November 1976, Toronto, Ontario.

Cihlar, J., R. Protz, I.P. Martini, and J.C. Acton. 1971. Report on ground truth information in the areas of geology, geomorphology and soils in Ontario for the IFTGL. Prepared for the Centre for Applied Research and Engineering Design, Project 154. 7 p.

Condit, H.R. 1970. The spectral reflectance of American soils. Photogrammetric Engineering 36:955-966.

Coulson, K.L. and D.W. Reynolds. 1971. The spectral reflectance of natural surfaces. Journal of Applied Meteorology 10:1285-1295.

Deardorf, J.W. 1977. A parameterization of ground-surface moisture content for use in atmospheric prediction models. Journal Applied Met. 16:1182-1185.

Estes, J.E., J. Jensen, L. Tinney, S. Atwater, T. Hardoin. 1976. Water demand studies in central California." In: An Integrated Study of Earth Resources in the State of California using Remote Sensing Techniques. NASA Grant #NGL05-003-404.

Gates, M. 1966. Characteristics of soil and vegetated surfaces to reflected and emitted radiation." Proceedings 3rd Symposium on Remote Sensing of Environment Univ. of Michigan, Ann Arbor.

Gausman, H.W. 1975. Leaf water content, pp. 1723-1724, In Manual of Remote Sensing (Reeves, R.G. (Ed.)). American Soc. of Photogrammetry, Falls Church, VA.

Heilman, J.L., E.T. Kanemasu, J.O. Bagley, and V.P. Rasmussen. 1977. Evaluating soil moisture and yield of winter wheat in the Great Plains using Landsat data. Remote Sensing of Environment 6:315-326.

Idso, S.B., R.J. Reginato, R.D. Jackson, B.A. Kimball, and F.S. Nakayama. 1974. The three stages of drying of a field soil. Soil Science Soc. of America Proceedings 38:831-837.

Idso, S.B., R.D. Jackson, and R.J. Reginato. 1975a. Detection of soil moisture by remote surveillance. American Scientist 63:549-557.

Idso, S.B., R.D. Jackson, R.J. Reginato, B.A. Kimball, and F.S. Nakayama. 1975c. The dependence of soil albedo on soil water content. Journal of Applied Meteorology 14:109-113.

Idso, S.B., R.J. Reginato, and R.D. Jackson. 1975d. Assessing bare soil evaporation via surface temperature measurements. In Hydrology and water resources in Arizona and the Southwest, Proceedings of the 1975 Meetings of the Arizona Section - American Water Resources Association and the Hydrology Section - Arizona Academy of Science 199-205.

Idso, S.B., T.J. Schmugge, R.D. Jackson, and R.J. Reginato. 1975e. The utility of surface temperature measurements for the remote sensing of soil water status. Journal of the Geophysical Research 80:3044-3049.

Idso, S.B., and W.L. Ehrler. 1976. Estimating soil moisture in the root zone of crops: a technique adaptable to remote sensing. Geophysical Research Letters 3:23-25.

Idso, S.B., R.D. Jackson, and R.J. Reginato. 1975b. Estimating evaporation: a technique adaptable to remote sensing. Science 189:991-992.

Idso, S.B., R.D. Jackson, and R.J. Reginato. 1976. Compensating for environmental variability in the thermal inertia approach to remote sensing of soil moisture. Journal of Applied Meteorology 15:811-817.

Idso, S.B., R.D. Jackson, and R.J. Reginato. 1977. Remote sensing of crop yields. Science 196:19-25.

Jackson, R.D., R.J. Reginato, and S.B. Idso. 1977. Wheat canopy temperature: a practical tool for evaluating water requirements. Water Resources Research 13:651-656.

Jackson, R.D., S.B. Idso, and R.J. Reginato. 1976. Calculation of evaporation rates during the transition from energy - limiting to soil - limiting phases using albedo data. Water Resources Research 12:23-26.

Janza, F.J., et al. 1975. Interaction mechanisms. Chapter 4 in: Reeves, R.G., (Ed.), Manual of remote sensing, American Soc. of Photogrammetry, Falls Church, VA 75-179.

Jet Propulsion Laboratory. 1976. "Landsat Follow-On: A Report by the Application Survey Groups." Technical Memorandum 33-803. Vol. II. NASA Contract #NAS7-100.

Kahle, A.B. 1977. A simple thermal model of the earth's surface for geologic mapping by remote sensing. Journal of Geophysical Research 83:1673-1680.

Kanemasu, E.T. 1974. Seasonal canopy reflectance patterns of wheat, sorghum, and soybean. Remote Sensing of Environment 3:43-47.

Kanemasu, E.T., L.R. Stone, and W.L. Powers. 1976. Evapotranspiration model tested for soybean and sorghum. Agronomy Journal 68:569-572.

Kanemasu, E.T., J.L. Heilman, J.O. Bagley, and W.L. Powers. 1977. Using Landsat Data to estimate Evapotranspiration of Winter Wheat. Env. Management 1:515-520.

Kauth, R.J., and G.S. Thomas. 1976. The tasselled cap--A Graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. Proc. Sympos. on Machine Processing of Remotely Sensed Data, Purdue Univ., 4B, p. 41-51. IEEE Cat. 76, CH1103-1-MPRSD.

Krinov, E.L. 1953. Spectral reflectance properties of natural formations. Technical Translation TT-439, National Research Council, Ottawa, Canada. 268p.

LaRocca, A.J. 1975. Methods of calculating atmospheric transmittance and radiance in infrared. Proceedings of the IEEE 63:75-94.

LARS, . 1970. Remote multispectral sensing in agriculture. Research Bulletin 873, Laboratory for Agricultural Remote Sensing, Purdue University. 112p.

LeSchack, L.A., N. Kerr Del Grande, S.I. Outcalt, J. Lewis, and C. Jenner. 1975. Correlation of dual-channel airborne IR data with soil moisture measurements. Final Report, Contract 4-35308, Development and Resources Transportation Co., Silver Spring, MD. 46 p.

Lidster, W.A., F. A. Schmer, D.W. Ryland and D.G. Moore. 1975. "Remote sensing techniques for determining water table depth in irrigated agriculture." Remote Sensing Institute, South Dakota State University, Brookings, SD.

Maxwell, J.R. 1976. Sensible characteristics of targets and backgrounds. Advanced Infrared Technology (Course Notes), University of Michigan. 76 p.

Millard, J.P., S.B. Idso, R.C. Goettelman, R.J. Reginato, R.D. Jackson, and W.L. Ehrler. 1977a. Airborne thermography for crop water stress assessment. Presented at the 6th Annual Conference on Remote Sensing of Earth Resources, Tullahoma, TN, March 1977.

Millard, J.P., R.D. Jackson, R.G. Goettelman, R.J. Reginato, S.B. Idso, and R.L. LaPado. 1977b. Airborne monitoring of crop canopy temperatures for irrigation scheduling and yield prediction. Proceedings of the 11th International Symposium on Remote Sensing of Environment, Ann Arbor, MI 1453-1461.

Moore, D.G., M.L. Horton, M.J. Russell, and V.I. Myers. 1975. Evaluation of thermal X/5-detector Skylab S-192 data for estimating evapotranspiration and thermal properties of soils for irrigation management. Proceedings of the NASA Earth Resources Survey Symposium, Houston, TX, NASA TM X-58168 2561-2583.

Moore, D.G. 1974. Soil Factor Influences Electromagnetic Radiation: Mapping Soil Features and Soil Moisture by Remote Sensing." Remote Sensing Institute, South Dakota State University, Brookings, SD.

Moore, D.G. 1974. Use of remote sensing to assess high water tables, groundwater and soil salinity. Remote Sensing Institute, South Dakota State University, Brookings, SD.

Myers, V.I., et al. 1975. Crops and soils. In Manual of remote sensing Vol. 2. American Society of Photogrammetry, Falls Church, VA. pp. 1715-1813.

Myers, V.I., and W.A. Allen. 1968. Electrooptical remote sensing methods as nondestructive testing and measuring techniques in agriculture. Appl. Opt. 7:1819-1837.

Myers, V.I. et al. 1970. Photographic detection of salinity, pp. 266-271, and thermal detection of salinity, pp. 271-274, In Remote Sensing with Special Reference to Agriculture and Forestry. Nat'l Acad. Sciences, Washington, D.C.

Myers, V.I., D.L. Carter, and W.J. Rippert. 1966. Remote sensing for estimating soil salinity. Journal Irrig. Drain. Div., Amer. Soc. Civil Eng. 92(IR4):59-68.

Nixon, P.R., L.N. Namken, and C.L. Wiegand. 1973. Spatial and temporal variations of crop canopy temperatures and implications for irrigation scheduling. In: Shahroki, F. (Ed.), Remote Sensing of Earth Resources, The University of Tennessee, Tullahoma, TN 643-657.

Obukhov, A.I., and D.S. Orlov. 1964. Spectral reflectivity of the major soil groups and possibility of using diffuse reflection in soil investigations. Soviet Soil Science 174-184.

Orlov, D.S. 1966. Quantitative patterns of light reflection by soils. I. Influence of particle (aggregate) size on reflectivity. Nauchnye Doklady Vysshey Shkoly, Biologicheskiye Nauki 206-210.

Outcalt, S.I. 1972. The development and application of a simple digital surface-climate simulator. Journal of Applied Meteorology 11:629-636.

Palmer, W.C. 1968. Keeping track of crop moisture conditions nationwide. The new crop moisture index. Weatherwise 21:156-161.

Price, J.C. 1977. Thermal inertia mapping: a new view of the Earth. Journal of the Geophysical Research 82:2582-2590.

Ragan, R.M. 1977. Utilization of remote sensing observations in hydrologic models. Proc. Eleventh Intern'l. Sympos. Remote Sensing of Environ. I:87-99.

Reginato, R.J., J.F. Vedder, S.B. Idso, R.D. Jackson, M.B. Blanchard, and R. Goettelman. 1977. An evaluation of total solar reflectance and spectral band ratioing techniques for estimating soil water content. Journal of Geophysical Research 82:2101-2104.

Reginato, R.J., S.B. Idso, J.F. Vedder, R.D. Jackson, M.B. Blanchard, and J. Goettelman. 1976. Soil water content and evaporation determination by thermal parameters obtained from ground-based and remote measurements. Journal of Geophysical Research 81:1616-1620.

Richardson, A.J., and C.L. Wiegand. 1977. A table look-up procedure for rapidly mapping vegetative cover and crop development. Proc. Sympos. on Machine Proc. of Remotely Sensed Data, Purdue Univ., pp. 284-297.

Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resources Res. 8:1204-1213.

Rosema, A. 1975. A mathematical model for simulation of the thermal behavior of bare soils, based on heat and moisture transfer. NIWARS - Publication No. 11, 3 Kanaalweg, Delft, The Netherlands.

Salomonson, V.V., and W.E. Marlatt. 1971. Airborne measurements of reflected solar radiation. Remote Sensing of Environment 2:1-8.

Saxton, K.E., H.P. Johnson, R.H. Shaw. 1974. Modeling evapotranspiration and soil moisture. Trans. AWAE 17:673-677.

Selby, J.E.A., and R.A. McClatchey. 1975. Atmospheric transmittance from 0.25 to 28.5 μm: Computer code LOWTRAN 3. AF Cambridge Research Laboratories, Bedford, MA 109p.

Sellers, W.D. 1965. Physical climatology. The University of Chicago Press, Chicago. 272p.

Sewell, J.I., and W.H. Allen. 1973. Visible and infrared remote sensing in soil moisture determination. In: Shahroki, F. (Ed.), Remote Sensing of Earth Resources II, The University of TN 689-702.

Steiner, D., and T. Guterman. 1966. Russian data on spectral reflectance of vegetation, soil and rock types. Juris Druck + Verlag Zurich. 232p.

Stockhoff, E.H., and R.T. Frost, 1971. Polarization of light reflected by moist soils. Proceedings of the 7th International Symposium on Remote Sensing of Environment, Ann Arbor, MI.

Stockhoff, E.H., R.T. Frost, and E.J. Buerger. 1973. Remote soil moisture measurements. Final Report under Contract NAS 5-21689, Space Sciences Laboratory, General Electric Co., Philadelphia, PA. 26p.

Sumayao, C.R., E.T. Kanemasu and T. Hodges. 1977. Soil moisture effects on transpiration and net carbon dioxide exchange of sorghum. Ag. Meteor. 18:401-408.

Tanner, C.B., and W.A. Jury. 1976. Estimating evaporation and transpiration from a row crop during incomplete cover. Agronomy Journal 68:239-242.

Thomas, J.R., and C.L. Wiegand. 1970. Osmotic and matric suction effects on relative turgidity, temperature and growth of cotton leaves. Soil Science 109:85-91.

Thomas, J.R., L.N. Namken, G.F. Oerther, and R.G. Brown. 1971. Estimating leaf water content by reflectance measurements. Agronomy Journal 63:845-847.

Thompson, D.R. 1976a. Results of LACIE integrated drought analysis (Southern U.S. Great Plains Drought 1975-76). Rpt. LACIE-00424 and JSC-11336.

Thompson, D.R. 1976b. Results of LACIE drought analysis (South Dakota Drought 1976). Rpt. LACIE-00437 and JSC-11666. Johnson Space Center. 33p.

Thompson, D.R., and O.A. Wehmanen. 1977. The use of Landsat digital data to detect and monitor vegetation water deficiencies. Proc. Eleventh Intern'l. Sympos. on Remote Sensing of Environ. II: 925-931. (Environmental Research Institute of MI, Ann Arbor).

Tucker, C.J. 1976. Sensor design for monitoring vegetation canopies. Photog. Eng. and Remote Sens. 42:1399-1410.

Von Minnus, E. 1967. Spektrale Remission Unbewachsener Bode als Faktor bei der Luftbildin-terpretation. Selbstverlag der Bundesanstalt fur Landeskunde and Raumforschung, Bad Godesberg. 41p.

Watson, K. 1975. Geologic applications of thermal infrared images. Proceedings of the IEEE 63:128-137.

Werner, H.D., F.A. Schmer, M.L. Horton, and F.A. Waltz. 1971. Application of remote sensing techniques to monitoring soil moisture. Proceedings of the 7th International Symposium on Remote Sensing of Environment, Ann Arbor, MI 1245-1258.

Wiegand, C.L., and L.N. Namken. 1966. Influences of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. Agronomy Journal 58:582-586.

Wiegand, C.L., M.D. Heilman, and A.H. Gerbermann. 1968. Detailed plant and soil thermal requirements in agronomy. Proceedings of the Fifth International Symposium on Remote Sensing of Environment, Ann Arbor, MI 325-241.

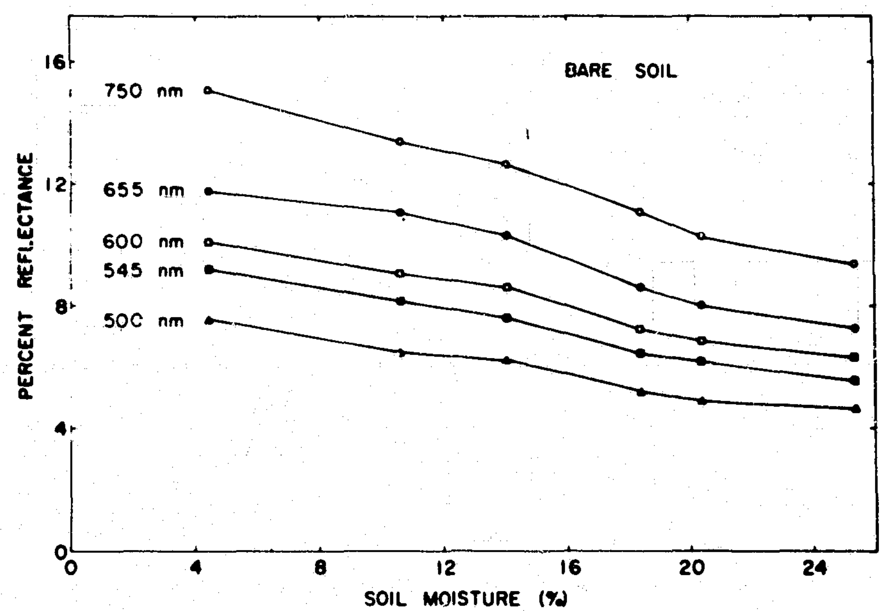

Fig. 4-1. Dependence of the midday spectral reflectance on soil moisture content (in percent by weight) for a bare silty clay loam field (from Kanemasu, 1974).

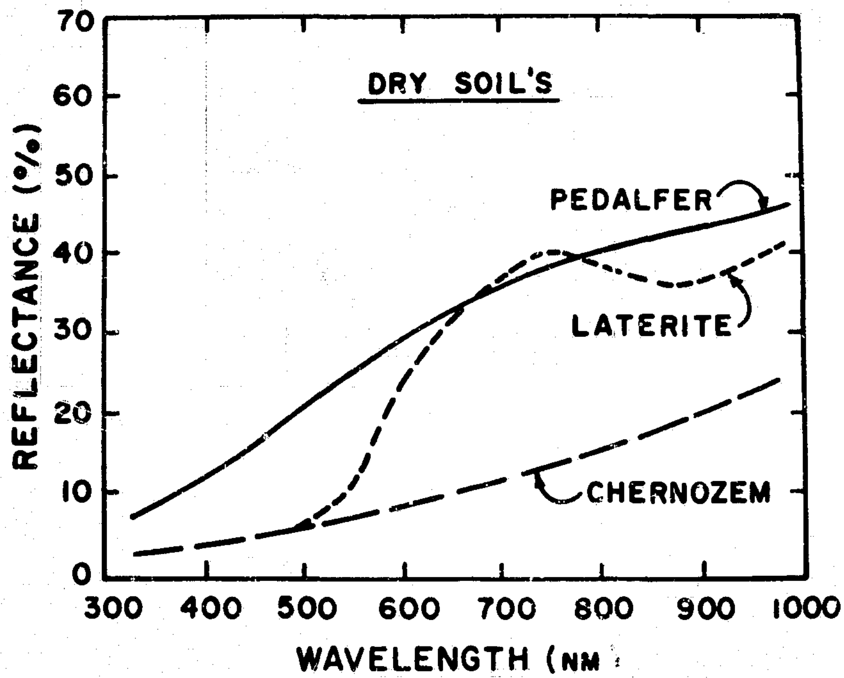

Fig. 4-2. Typical spectral reflectance of dry soils as a function of wavelength (after Condit, 1970).

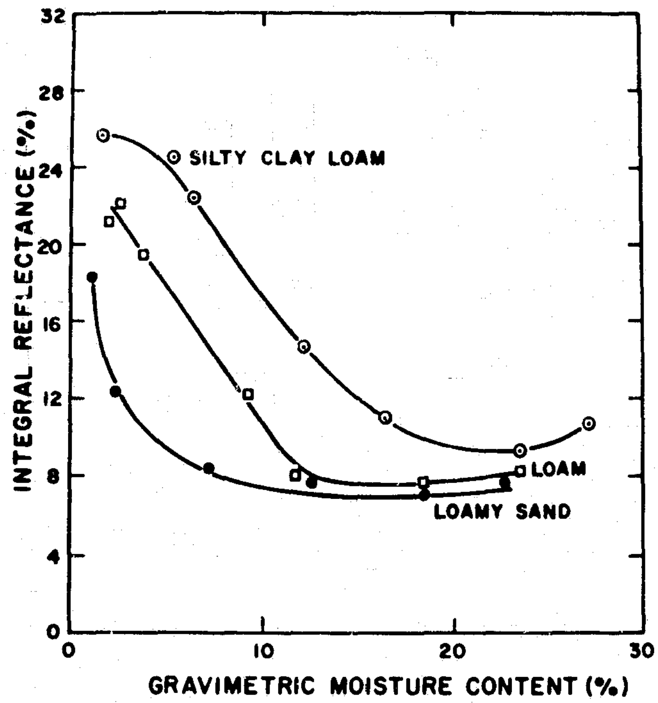

Fig. 4-3. Total reflectance (0.38 to 0.78 μm) as a function of gravimetric moisture content for three southern Ontario soils (after Cihlar et al., 1971).

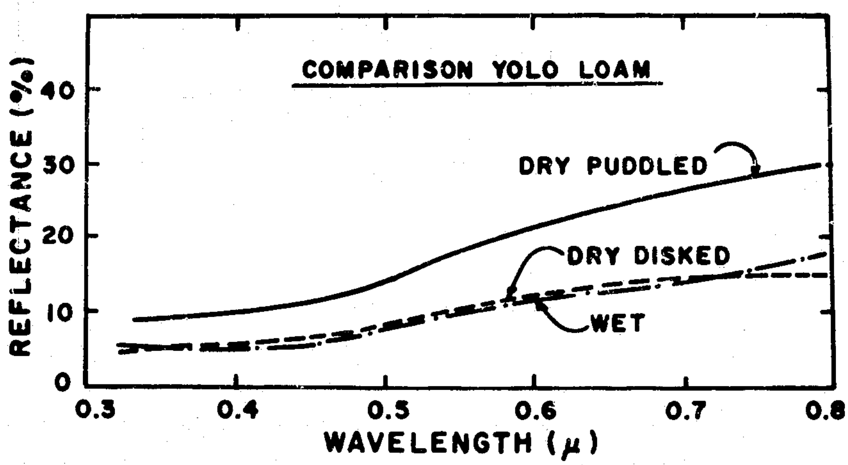

Fig. 4-4. Directional spectral reflectance of a bare Yolo loam field under three surface conditions. Measurements were made for a solar zenith angle $\theta = 30°$ (after Coulson and Reynolds, 1971).

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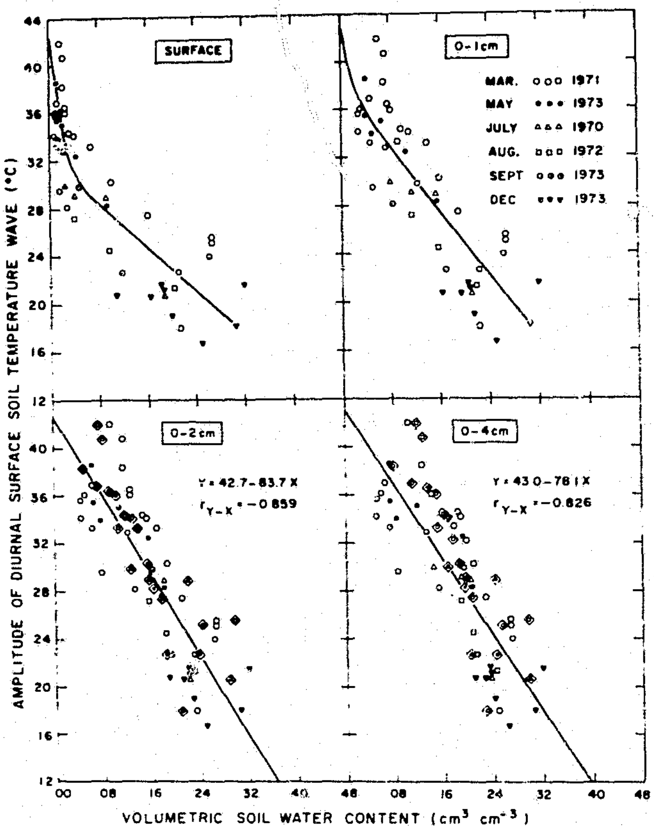

Fig. 4-5. The amplitude of diurnal soil surface temperature wave (Ts, max - TS, min) plotted against the mean daylight volumetric water content for clear day-night periods; soil was bare Avondale loam (from Idso et al., 1975).

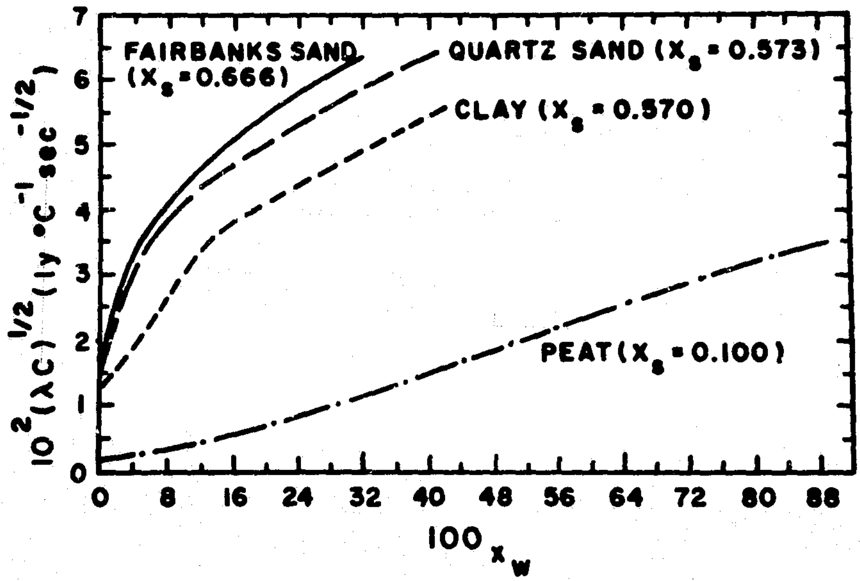

Fig. 4-6. Thermal inertia of various materials as a function of the volume fraction of water (after Sellers, 1965).

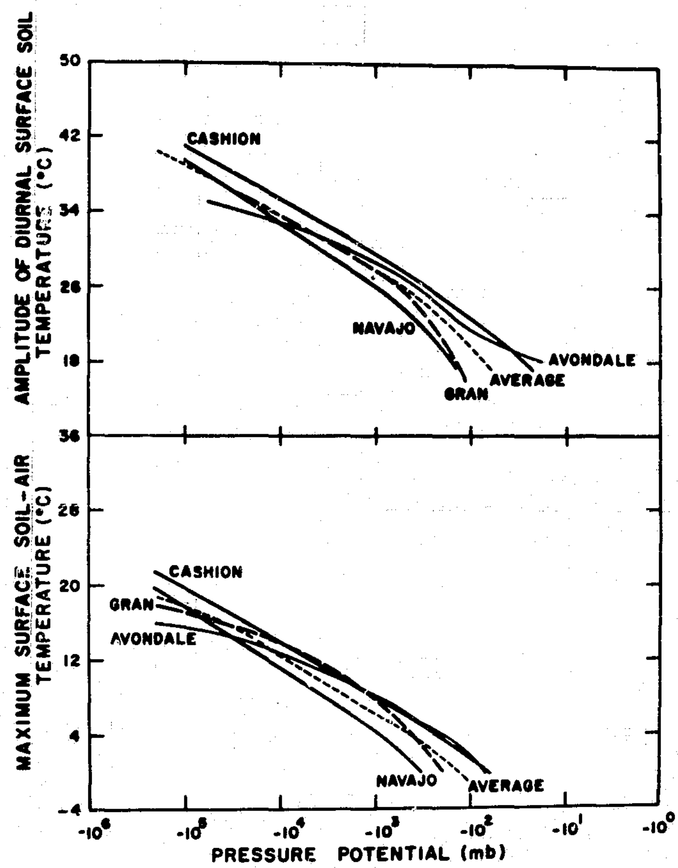

Fig. 4-7. The amplitude of diurnal soil surface temperature wave (Ts, max - Ts, min) and the difference between maximum surface and air temperatures (Ts, max - Ta, max) plotted against pressure potential of soil water (0 to 2 cm depth) bare soils with various textures (from Idso et al., 1975a).

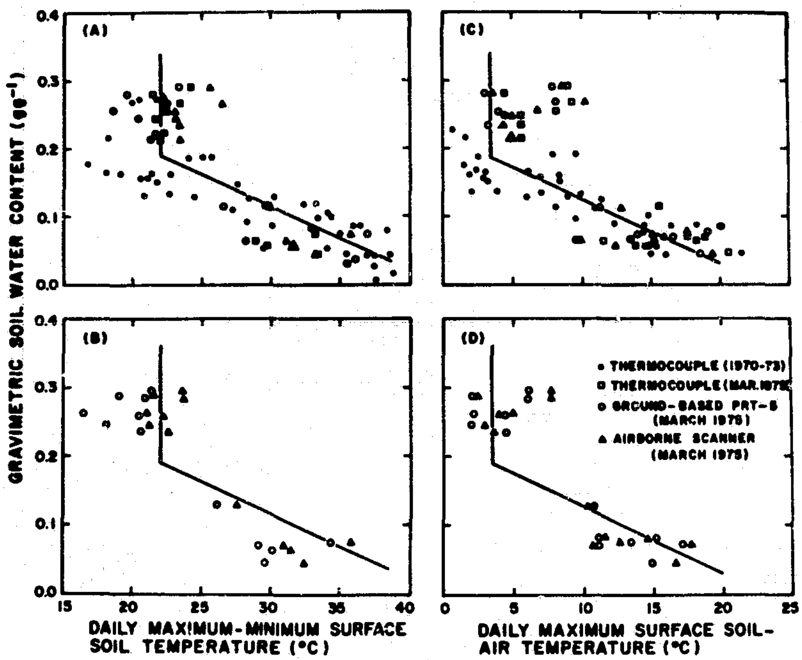

Fig. 4-8. Daily average gravimetric soil water content in the surface 0- to 2-cm layer of bare Avondale loam versus daily maximum minus minimum surface soil temperature for (a) smooth soil and (b) rough soil and versus daily maximum soil minus air temperature for (c) smooth soil and (d) rough soil (from Reginato et al., 1976).

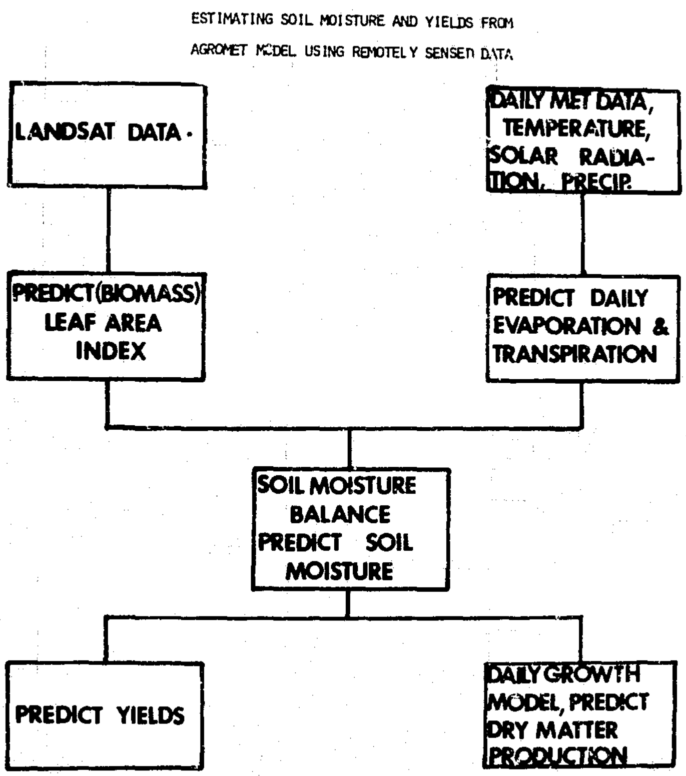

Fig. 4-9. Flow diagram for Agromet model.

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CHAPTER 5

MICROWAVE AND GAMMA RADIATION OBSERVATIONS OF SOIL MOISTURE

CONTRIBUTORS

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A. INTRODUCTION

The unique dielectric properties of water at microwave wavelengths afford the possibility for remotely sensing the moisture content in the surface layer of the soil. The dielectric constant for water is an order of magnitude larger than that of dry soils at microwave wavelengths ($50>\lambda>1$ cm). As a result, the surface emissivity and reflectivity for the soils at these wavelengths are strong functions of its moisture content. The changes in emissivity can be observed by passive microwave techniques (radiometry) and the changes in reflectivity can be observed by active microwave techniques (radar).

Both of these approaches, active and passive microwave, have been demonstrated in extensive field and aircraft measurements. Correlations of 0.8 to 0.9 have been obtained between soil moisture in the surface layer (~5 cm thick) and microwave brightness temperature T_B or radar backscatter coefficient σ^o. These microwave techniques maintain their sensitivity to soil moisture variations in the presence of a moderate crop canopy. Qualitative observations of the passive microwave sensitivity have also been made from satellite platforms at wavelengths of 21 and 1.55 cm. Thus, it appears to be possible to monitor the moisture status of the surface soil using these techniques.

Although these microwave techniques have demonstrated the capability to measure soil moisture content over a wide range of surface conditions, including roughness and vegetation cover, with a measurement precision comparable to that associated with in-situ measurements, several developmental steps have to be accomplished before they can be used for global monitoring of soil moisture content. These steps may be divided into two groups. The objective of the first group of steps is to extend the experimental results to large area coverage with aircraft and spacecraft measurements. The second group of steps pertains to the requirements of the intended user of the soil moisture information. The system design specifications will be impacted by the answers to specific questions regarding spatial resolution, soil moisture depth information, and frequency of coverage, which are needed from the user community.

The difference in the natural terrestrial gamma ray flux measured for wet and for dry soil may be used for the determination of soil moisture. The gamma flux originates primarily from radio isotopes in the soil, principally potassium (40) and the decay products in the uranium and thorium series. It has been reported that 91 percent of the gamma rays emanating from a natural soil come from the top 10 cm and 96 percent from the top 20 cm. The presence of moisture in the soil causes an effective increase in soil density, resulting in an increased attenuation of the gamma flux for wet soil and a corresponding lower flux above the ground surface.

B. SOIL DIELECTRIC PROPERTIES

A number of soil dielectric constant measurements have been made in recent years as functions of moisture content, frequency and soil type (e.g. Leschanskii et al., 1971; Lundien, 1971; Wiebe, 1971; Hipp, 1974; Hoekstra and Delaney, 1974; Njoku and Kong, 1977). A compilation of some of the earlier measurements is found in the report by Cihlar and Ulaby (1974). Figure 5-1 shows the dependence of the real and imaginary parts of the dielectric constant as functions of moisture content at wavelengths of 1.55 and 21 cm. There is some difference between the dielectric constants measured for different soil types when plotted against moisture percent by weight especially at the longer wavelengths (Fig. 5-1). This is due to the different strengths by which water molecules adhere to the soil particles. Thus when plotted against soil water matric potential the dielectric constant becomes essentially independent of soil type (Newton, 1976). For this reason brightness temperature data are often plotted as a function of percentage field capacity (which is directly related to soil water matric potential)(Schmugge, 1976). This is further desirable because matric potential (and percentage field capacity) are parameters that describe the water availability to plants and the degree of soil saturation, which are of primary importance to agriculturalists and hydrologists.

The range of dielectric constants presented in Fig. 5-1 produces a change in emissivity from greater than 0.9 for a dry soil to less than 0.6 for a wet soil, assuming an isotropic soil with a smooth surface. This change in emissivity for a soil has been observed by truck mounted radiometers in field experiments (Poe, 1971; Newton, 1976), and by radiometers in aircraft (Schmugge, 1974) and satellites (Eagleman, 1976). In no case were emissivities as low as 0.6 observed for real surfaces.

It is believed that this is primarily due to the effects of surface roughness.

As can be seen in Fig. 5-1 there is a greater range of dielectric constants for soils at the 21 cm wavelengths. This fact combined with a larger soil moisture sampling depth and better ability to penetrate a vegetative canopy make the longer wavelength sensors better suited for soil moisture sensing.

C. PASSIVE MICROWAVE RESPONSE TO SOIL MOISTURE

1. Physical Basis

A microwave radiometer measures the thermal emission from the surface, and at these wavelengths the intensity of the observed emission is proportional to its brightness temperature (Rayleigh-Jeans approximation). The brightness temperature T_B observed by a radiometer from a height above the surface is:

$$T_B = \tau[rT_{sky} + T_e] + T_{atm} \qquad [5\text{-}1]$$

The term in brackets includes the reflected component of the downwelling sky brightness temperature (cosmic background plus atmospheric contribution) and the brightness temperature of the radiation emitted by the earth's surface. These are modified by the transmittance τ of the layer of atmosphere between the surface and the radiometer. The final term in the expression is the contribution of this layer of atmosphere to the upwelling radiation reaching the radiometer. At the longer wavelengths, i.e. those best suited for soil moisture sensing, the atmospheric effects are minimal and will be neglected in this discussion.

Thermal microwave emission from soils is generated within the soil volume. The amount of energy generated at any point within the volume is dependent on the soil dielectric properties (or soil moisture) and the soil temperature at that point. As energy propagates upward through the soil volume from its point of origin, it is affected by the dielectric (soil moisture) gradients along the path of propagation. In addition, as the energy crosses the surface boundary it is reduced by the effective transmission coefficient which is determined by the dielectric characteristics close to the surface.

The brightness temperature of the surface can be written in terms of an integral over the half-space (Njoku and Kong, 1977)

$$T_B = \int_{-\infty}^{0} T(z)\ F[\varepsilon_r(z)]\ dz \qquad [5\text{-}2]$$

where $T(z)$ is the subsurface temperature profile and $\varepsilon_r\ (z)$ is the dielectric constant profile. $F[\varepsilon_r\ (z)]$ is in the form of a weighting function which includes the effects of the surface reflectivity. The depths from which the emitted radiation originates and its radiation temperatures are governed by the relative shape of the weighting function, which in turn depends primarily on the dielectric loss profile. The magnitude of the weighting function is dependent on the surface reflectivity, which in most cases is governed by the dielectric properties in a region close to the surface. The depth of this region and the subsurface extent of the weighting function are frequency dependent, thus lower frequencies are sensitive to dielectric properties at greater depths in the soil. Further theoretical and experimental work is needed to determine the dependence of the "sensing depth" on frequency and moisture profile.

When $T(z)$ is uniform, the weighting function integral can be evaluated to give the emissivity, e, which is related to the surface reflectivity, r. The brightness temperature can then be written as:

$$T_B = T \int_{-\infty}^{o} F[\varepsilon_r(z)]\, dz \qquad [5\text{-}3]$$

or

$$T_B = eT = (1-r)T \qquad [5\text{-}4]$$

For a smooth surface the emissivity can be approximated to a high degree of accuracy using numerical techniques for a layered medium. This expression for brightness temperature is widely used and is sufficiently accurate for most applications. In areas where a large subsurface increase or decrease of temperatures occurs over the region defined by the weighting function an average temperature must be used for T rather than the surface temperature.

The presence of soil moisture causes a marked change in soil dielectric properties, resulting in a decrease in emissivity over that of a dry soil. In addition to the presence of moisture, surface roughness and vegetation cover also have significant effects, generally tending to increase the surface emissivity.

2. Ground Based Experiments

Measurement programs utilizing ground-based radiometers have been performed for a number of years. The more comprehensive measurement programs have been executed by Aerojet-General Corporation (Poe, et al., 1971), Jet Propulsion Laboratory (Blinn and Quade, 1972) and Texas A&M University (Newton, 1976; Newton and Tesch, 1976; Newton et al., 1974).

In Fig. 5-2(a) and (b) the field measurements of Newton (1976) are plotted versus angle of observation for various moisture contents and for three levels of surface roughness. The horizontal polarization is that for which the electric field of the wave is parallel to the surface and the vertical polarization is perpendicular to it. These results indicate the effect of moisture content on the observed values of T_B and the effect of surface roughness, which is to increase the effective emissivity at all angles and to decrease the difference in T_B for the two polarizations at the larger angles. Thus, by making the polarization measurements it may be possible to separate the effects of surface roughness and soil moisture.

For the smooth field there is a 100° K change in T_B in going from wet to dry soils and it is clear that this range is reduced by surface roughness. The effect of the roughness is to decrease the reflectivity of the surface and thus to increase its emissivity. For a dry field the reflectivity is already small (<0.1) so that the resulting increase in emissivity is small. As seen in Figure 2b surface roughness has a significant effect for wet fields where the reflectivity is larger ($\simeq 0.4$). Thus the range of T_B for the rough field is reduced to about 60° K. The smooth and rough fields represent the extremes of surface conditions that are likely to be encountered, e.g. the rough surface was on a field with a heavy clay soil (clay fraction >60%) that had been deep plowed which produced large clods. Therefore the medium rough field, with a T_B range of 80° K, is probably more representative of the average surface roughness condition that will be encountered. Another important observation from Fig. 2a and b is that the average of the vertical and horizontal T_B's is essentially independent of angle out to 40°. This indicates that the sensitivity of this quantity, $1/2(T_{BV} + T_{BH})$, to soil moisture will be independent of angle. This factor will be useful if the radiometer is to be scanned to provide an image.

When the brightness temperatures for the medium rough field are plotted versus soil moisture in the 0-2 cm layer there is an approximate linear decrease of T_B (Fig. 5-3a). As the thickness of the layer increases both the slope and intercept of the linear regression result also increase. This is because the moisture values for the high T_B cases increase while it remains essentially the same for the low T_B or wet cases. This type of behavior was also seen in the results obtained from aircraft platforms and has led us to conclude that the soil moisture sampling depth is in the 2-5 cm range for the 21 cm wavelength. This is in agreement with the predictions of theoretical results for radiative transfer in soils (Wilheit, 1975; Burke and Paris, 1975).

The effect of a vegetative canopy will be that of an absorbing layer that depends on the amount of the vegetation and the wavelength of observations. In Fig. 5-3b the results for a closely planted sorghum field (~1 m high) are presented.

The range of T_B is now about 40 K compared to the 70 K range observed for the bare field. While the sensitivity to the soil moisture variation is reduced, the correlation remains high (~0.9). At a shorter wavelength (2.8 cm) there is only a 10 K range in T_B in going from wet to dry. While these measurements show that a radiometer operating at 21 cm still has good sensitivity to soil moisture variations, they suggest that radiometers working at longer wavelengths (30 to 50 cm) may have better sensitivity.

3. Aircraft and Satellite Experiments

Significant improvements in the understanding of the effects of individual scene parameters on the relationship of brightness temperature to soil moisture have been achieved using ground-based measurements acquired during controlled experiments. However, demonstration of the potential of passive microwave sensors for estimating soil moisture on an operational basis must be performed with aircraft and spacecraft sensors that integrate large areas of natural, non-idealized terrain. A series of aircraft experiments performed over the last several years by a number of investigators demonstrates the sensitivity of microwave radiometers to soil moisture in agricultural terrain. Skylab and Nimbus satellites have also provided significant results for very large areas of integration.

The results from aircraft experiments are summarized in Fig. 5-4 where results from aircraft flights in February 1973 (Fig. 5-4a) and March 1975 (Fig. 5-4b) over Phoenix, Arizona are presented (Schmugge, 1976). The values are plotted versus soil moisture expressed as a percent of field capacity to normalize the effect of soil texture differences. The agreement of the slopes for the three regressions indicates that the results are repeatable. The differences for the intercepts in

Fig. 5-4b are due to differences in soil temperature between the 1975 a.m. and p.m. results. The range of T_B of each case is in good agreement with the medium rough field results presented in Fig. 5-3.

In Fig. 5-4c the results from vegetated fields for the two years are presented. The vegetation was either alfalfa or wheat with wheat being 20-30 cm high in 1973 and 50-60 cm high for the 1975 data. The slope of the curve is in good agreement with those for the bare fields. The intercept is lower due to the cooler soil temperatures. Thus sensitivity to soil moisture is maintained through the moderate vegetative canopies considered here, which were approximately one half the height of the sorghum canopy considered in Fig. 5-3b.

A further demonstration of the capability of this sensor is presented in Fig. 5-5. Here the results from 5 flights during 1976 and 1977 over a Hand County South Dakota test site are compared with the regression result from the Phoenix data. The agreement is very good. These data were for a range of surface conditions including fallow fields, wheat, alfalfa and pasture. The scatter in the aircraft data presented in Fig. 5-4 and 5-5 arises from a number of sources, one of which is surface roughness as demonstrated in Fig. 5-3b; another is the uncertainty of ground measurements. The standard deviation of the ground measurements is represented by the error bars in Fig. 5-5. The number of samples ranged from 6 to 29 depending on the length of the fields. This difficulty of making accurate ground measurements has hampered the determination of the accuracy of this measurement technique.

Studies of the Nimbus-5 satellite Electrically Scanning Microwave Radiometer (ESMR) data at 1.55 cm wavelength have shown that it has limited applicability for soil moisture sensing (Meneely, 1977). The limitation is primarily caused by a vegetative canopy over the soil. For situations where there is a significant amount of bare ground the ESMR brightness temperature has shown significant correlations with soil moisture (McFarland and Blanchard, 1977; Schmugge et al., 1977). These situations arise in agricultural areas before the crops are planted and during the early stages of growth.

Studies using the 21 cm data obtained by the S-194 instrument on board Skylab have shown significant correlations with soil moisture variations. The latter were determined either by moisture budget models (Eagleman and Lin, 1976) or by using the antecedent precipitation index (McFarland, 1976). This was a limited data set and its interpretation was hampered by the coarse spatial resolution (~115 km) of the sensor. However, the results are encouraging for the potential use of a sensor operating at this wavelength for soil moisture sensing. Improved spatial resolution can be obtained by using larger antennas. The antenna on the Skylab instrument was 1 m square. In the future it should be possible to deploy much larger antennas from the space shuttle and for example a 10 m antenna would yield resolutions in the 10 km range.

D. ACTIVE MICROWAVE RESPONSE TO SOIL MOISTURE

1. Physical Basis

Analogous to the optical reflectivity of terrain, the backscattering coefficient σ^o describes the scattering properties of terrain in the direction of the illuminating source. The scattering behavior of terrain is governed by the geometrical and dielectric properties of the surface (or volume) relative tc the wave properties (wavelength, polarization, and angle of incidence) of the incident illumination. Recall that the dielectric constant of a soil-water mixture is strongly dependent on its water content. Thus, in general, σ^o of terrain is dependent on the soil moisture content of an effective surface layer whose thickness is governed by the penetration properties of the terrain at the wavelength used; this thickness will be approximately the same for active and passive microwave approaches. In addition to its dependence on soil moisture content, however, σ^o is also in general a function of the surface (or volume) roughness and vegetation or snow cover (if not bare).

From an operational system standpoint, radar possesses two key capabilities of major importance to remote sensing applications, namely a) its ability to make timely observations unhampered by cloud cover or time of day which may be a very critical factor in hydrologic modeling, and b) its ability to generate high resolution imagery from space platforms. Recognizing these system capabilities and the dependence of the soil dielectric constant on its moisture content, a research program was initiated at the Remote Sensing Laboratory of the University of Kansas in 1972 under NASA/JSC sponsorship to evaluate the potential use of radar for monitoring soil moisture content. The major objectives of the program are:

a) To determine if a set of sensor parameters (wavelength, polarization and angle of incidence range) can be specified such that such a sensor can measure soil moisture content with acceptable precision, independently of surface roughness and vegetation cover.

b) To relate the observed σ^o to an effective depth representing the depth of the soil layer responsible for the observed σ^o.

c) If (a) is feasible, to determine what additional system and terrain considerations should be incorporated into the design configuration of a radar soil moisture sensor, and to evaluate its performance relative to the needs defined by the user community.

2. Ground-Based Results

Over the past six years, the radar response to soil moisture content was extensively investigated by the University of Kansas using truck mounted Microwave Active Spectrometer (MAS) systems (Ulaby, 1974; Ulaby et al., 1974 and 1975; Batlivala and Ulaby, 1977). The sensitivity to soil moisture content and the accuracy and precision with which it can be estimated were evaluated for both bare and vegetated fields.

a. Bare Ground

The objective of the bare field experiments was to determine the optimum radar parameters for minimizing the response to surface roughness while retaining strong sensitivity to moisture content. By examining the radar response to soil moisture of several fields with considerably different surface roughness conditions ranging from very smooth (dragged) to very rough (disked), the following set of optimum parameters was determined: λ = 6-7 cm, $\theta = 7^o - 17^o$ from nadir, and horizontal transmit-horizontal receive polarization (Ulaby and Batlivala, 1976). Figure 5-6 shows the response in this range of sensor parameters. Included are data for all fields, regardless of surface roughness. Also shown on the figure are the calculated error ranges corresponding to ±1 standard deviation associated with the measurement of σ^o and the in-situ measurement of m_1, the moisture content in the top 1 cm of the soil. A statistical analysis of these variances indicates that at these optimum parameters, the error (due to surface roughness) associated with the soil moisture estimate provided by such a radar system is comparable to the error associated with the in-situ measurement of m_1 (Ulaby and Dobson, 1977).

Because the moisture content in a given soil layer is correlated to the moisture content of the other layers in the profile, it is difficult to experimentally separate the contributions of the remaining layers to the observed backscatter. Figure 5-7 is a plot of the linear correlation coefficient $\rho(\sigma^o, m_x)$ between σ^o and m_x where mx is the moisture in the 0 to x cm layer. It is observed that (σ^o, m_x) is not very sensitive to the depth interval x, particularly for the bare soil case. Thus, based on the above, one may conclude that σ^o is sensitive to moisture down to at least 9 cm. Such a statement may be erroneous, however, since part of the observed correlation is due to the correlation between the moistures in the different levels. Theoretical and experimental approaches are currently under investigation to develop an algorithm that can better relate the observed σ^o to an effective depth interval than is presently possible.

In addition to surface roughness, another soil variable that has exhibited an influence on the σ^o response to moisture is soil texture. Figure 5-8a presents plots of two linear regression lines based on experimental measurements acquired in 1974 at a test site near College Station, Texas, and in 1975 at a site near Lawrence, Kansas. The 1974 soil was Miller clay with 49% clay content whereas the 1975 soil was Eudora silt loam with only 17.2% clay content. The two regression lines show a substantial difference in sensitivity (slope). A similar difference in sensitivity due to soil texture was observed by Schmugge et al. (1976), in their study of the passive microwave response to soil moisture. Airborne data acquired over test sites located near Phoenix, Arizona and in Imperial Valley, California, showed a weaker sensitivity to moisture content of heavy soils (high clay content) than for light soils. To incorporate soil texture in the microwave response to soil moisture, the latter was expressed in terms of percent of field capacity m_{fc}. The same conversion to percent of field capacity used by Schmugge et al. (1976) was applied to the radar data of 1974 and 1975 and the resulting regression lines are shown in Fig. 5-8b, which are much closer to one another than those in Fig. 5-8a. Although these results suggest that the dependence of σ^o on soil texture can be removed by expressing moisture content in percent of field capacity, it was decided that a detailed experiment covering a wide range of soil texture should be performed before the role of soil texture can be well established. Such an experiment was performed during the summer of 1977, but the results are not yet available.

b. Vegetation-Covered Ground

The presence of a vegetation canopy over the soil surface reduces the sensitivity of the radar backscatter to soil moisture by a) attenuating the signal as it travels through the canopy down to the soil and back and by b) contributing a backscatter component of its own. Moreoever, both factors are in general a function of several canopy parameters including plant shape, height and moisture content, and vegetation density. The effect of the vegetation cover on the radar response to soil moisture is shown in Fig. 5-9 where the bare soil and vegetation-covered responses are plotted as a function of percent field capacity in the top 5 cm. The vegetation-covered response represents data for several crops covering the wide range of growth conditions listed in Table 5-1 (Ulaby, et al., 1977).

Figure 5-10 shows the variation of σ° and m_5 (moisture in the 0-5 cm layer) as a function of time over a period of two months for a field planted in soybeans. Over the observation period, the soybeans canopy grew in height from 0.4 m to 0.7 m. The σ^o variation is clearly in response to m_5. Similar behavior was observed for other crops.

Table 5-1

1975 Vegetation Cover Experiment

Crop Type	Number of Data Sets	Duration of Measurements	Variation of Crop Height
Wheat	46	May 19 - July 9	60 cm - 120 cm
Corn	59	May 23 - Sept. 9	15 cm - 300 cm
Soybeans	53	July 9 - Sept. 8	33 cm - 80 cm
Milo	24	July 16 - Sept. 10	90 cm - 113 cm

3. Aircraft and Spacecraft Results

Although no detailed airborne investigations have yet been reported on the active microwave response to the soil moisture content underneath a vegetation canopy, an observation was made of the difference between dry soil and soil undergoing irrigation in 1971 while conducting radar observations of agricultural fields. During a flight by the NASA/JSC P3A aircraft over a test site near Garden City, Kansas, measurements were acquired by a 13.3 GHz scatterometer from several fields each of which was found (from aerial photography and field crew's reports) to contain sections into which irrigation water was flowing and sections ready for irrigation but not yet wetted (Dickey, et al., 1974). For each of these fields, the effect of the irrigation on the radar return appeared to produce a difference of about 7 dB at angles within 40° from nadir. An example is given in Fig. 5-11a (Dickey, et al., 1974) where the measured σ^{0} curves for the irrigated and non-irrigated sections of a corn field are shown. Since all ground conditions, except for soil water content, were similar over the entire field, the differences in σ^{0} can only be attributed to the effect of moisture.

The test site consisted of 706 fields, of which, on the basis of ground truth information, 687 were judged as dry and 19 were judged as wet. Some of the fields in the test site were bare ground while the majority were planted with corn, sorghum, alfalfa, sugar beets and wheat. Figure 5-11b shows the average σ^{0} curves for each of these two sets as a function of incidence angle (Dickey, et al., 1974). The results clearly demonstrate the capabilities of radar in separating dry terrain from wet terrain under a variety of vegetation cover.

In conjunction with Skylab passes over test sites in Texas and Kansas, soil samples were acquired to correlate their moisture contents with the active and passive microwave measurements acquired by the Skylab sensors (Eagleman, 1975). Although the calculated correlation coefficient between σ^0 and moisture content was as high as 0.75 for one of the passes, the results cannot be considered reliable because of the poor representation of the 13 Km x 16 Km elliptically shaped footprint by a few soil samples.

E. DISCUSSION

It is anticipated that over the next several years experiments will be conducted and theoretical models developed and tested to provide more accurate answers to the following questions concerning our measurements capabilities:

a) What is the dependence of the microwave response to soil moisture on soil texture?

b) Can the microwave response be unambiguously related to the moisture content of a specific soil depth?

c) Will longer wavelength passive systems yield a greater soil moisture sampling depth with less sensitivity to surface roughness and vegetation cover?

d) If soil moisture in the top few centimeters of the soil can be measured through remote sensing, how well can hydrologic models predict moisture at deeper levels? And what is the needed revisit interval?

Information on the spatial and temporal variations of soil moisture are useful to a variety of disciplines including hydrology, crop yield forecasting and meteorology. The requirements of these different disciplines can vary extensively.

The definition of a microwave soil moisture sensor will depend to a large extent on what these disciplines see as their needs for soil moisture information in terms of such things as frequency of coverage, spatial resolution, and observation strategy.

a) Revisit Interval. Soil moisture content is a dynamic variable; it is influenced by precipitation, evaporation (or evapotranspiration), runoff and infiltration. The frequency at which this variable should be sampled (in order to meet the needs of the user) influences the choice of spacecraft altitude and type of sensor. Assuming that a microwave sensor can make an accurate measurement of the soil moisture in the top 5 cm, how frequent should this measurement be made?

b) Resolution. Active microwave techniques can produce very high resolution (e.g. 50 m) imagery. The higher the resolution, however, the higher is the cost. The cost of the instrument itself may be small when compared to the costs incurred in processing, telemetering, reducing, and interpreting the data generated by an operational system. Passive microwave techniques on the other hand can provide wide swath coverage with coarse resolution (e.g. 10 Km) at much lower costs with respect to data handling and processing. Hence, the resolution of an operational soil moisture system should be specified as a result of a cost-benefit analysis of the intended applications, keeping in mind that reduction in resolution means reduction in cost as well as a possible reduction in the accuracy and precision of the soil moisture estimate. The presence of resolvable cultural features and small lakes and ponds can be accounted for on a high resolution image (50 m x 50 m cell size, for example), while on a low resolution image, unresolvable features can bias the integrated return from a given cell, thereby reducing the accuracy of the soil moisture estimate.

c) Observation Strategy. The different characteristics of the active and passive microwave sensors provide two options for observation strategies. The passive system with its wide swath capability can provide frequent total coverage with the coarse resolution, while the active system with a limited swath width would be able to provide frequent coverage for limited areas on a sampling basis. The various applications for soil moisture data will undoubtedly have different requirements on the spatial and temporal resolutions of the data. Therefore it would be good to learn how the different users would view these two options in their potential application of soil moisture data.

We expect that this workshop in providing some answers to these questions will be a great benefit in defining our future experimental program.

F. GAMMA RADIATION

Determination of soil moisture using gamma radiation is based on the attenuation of the natural terrestrial gamma-ray flux by the moisture in the soil. Most of the gamma radiation from naturally occurring radio-elements in the soil, measured above ground, originates within a few inches of the surface. The presence of moisture in the soil increases effective soil density, resulting in an increased attenuation of the gamma flux for wet soil and a corresponding lower flux above the ground surface. Gravimetric analysis of a few selected samples of the surface soil, provides calibration data to allow a quantitative determination of aerial measurements over a wide area.

Predominant gamma rays from natural radioelements in the soil include the 2.6 MeV ^{208}Tl gammas from the thorium decay chain, a family of ^{214}Bi gammas from the uranium decay chain ranging over values of 0.61, 0.76, 0.93, 1.12, 1.76 and 2.2 MeV, and the 1.46 MeV gammas from ^{40}K. The gamma counts under the ^{208}Tl photopeak contain no background contribution from the airborne ^{214}Bi radon daughters. The gross count data, integrated over the range between 50 keV and 3.0 MeV offers the advantage of excellent counting statistics and good spatial resolution (on a mile-by-mile basis), but contains a significant amount of background counts from radon daughters. Correction for airborne radon contributions are most often achieved by air filter data analysis.

Analysis of all three parameters, gross gamma counts, ^{40}K photopeak area, and ^{208}Tl photopeak area can be used independently to determine soil moisture values. All three methods involve a measured reduction in the gamma flux from the terrestrial surface as a consequence of increased soil density due to the presence of moisture. The ratio of gamma flux Γ_1/Γ_2 measured for two different soil moisture conditions M_1 and M_2 has the form

$$\frac{\Gamma_1}{\Gamma_2} = \frac{1 + M2}{1 + M1} \qquad [5\text{-}5]$$

The gamma count rates in the photopeaks for ^{40}K and ^{208}Tl can be determined by subtracting the non-terrestrial background counts (due to the aircraft, cosmic rays and airborne radon daughters) from the respective pulse height spectrum windows. These net photopeak count rates can be adjusted to correspond to that for transport of these terrestrial gammas through an air mass equivalent to the aircraft altitude. Soil moisture values can be computed from the photopeak area data using the relationship given in equation [5-5].

The third method of determining soil moisture from aerial measurements of terrestrial gamma radiation uses analysis of gross gamma count rates between 30 keV and 3.0 MeV. If the airborne radon daughter contribution to the signal is negligible, the net terrestrial gross count rate is determined by subtracting the gamma background count rate due to the aircraft and cosmic rays. The net gamma count rate is then adjusted to correspond to that for transport of these terrestrial gammas through an air mass equivalent to aircraft altitude. Often, however, substantial airborne radon daughters are present during the surveys and corrections are required. In studies by EGG for NOAA/NESS at Phoenix, Arizona, and Luverne, Minnesota, good agreement was obtained between aerial estimates of soil moisture and ground-based sampling. However, the low altitudes required (~150m) may limit the usefulness of this technique for large-area surveys of soil moisture. Gamma radiation techniques may be useful as a method of obtaining ground-truth and calibration information for other sensors.

G. KEY-POINT SUMMARY

Following is a summary of key points and recommendations concerning microwave and gamma ray sensing of soil moisture.

* Theoretical and experimental work should be conducted to determine the dependence of the sensing depth on frequency and moisture profile characteristics.

* Optimum angles of incidence and frequencies for identifying and reducing effects of surface roughness and vegetation should be determined.
* Theoretical models appropriate for soil moisture measurement problems should be developed. Modeling research should be multispectral (visible, IR, active and passive microwave).
* Effects of soil characteristics on the microwave response to soil moisture should be evaluated.
* The potential of passive and active microwave sensors should be demonstrated for estimating soil moisture on an operational basis with aircraft and spacecraft sensors that integrate large areas of natural, non-idealized terrain.
* Gamma radiation technology should be utilized for calibration and ground truth purposes.

H. BIBLIOGRAPHY

Batlivala, P.P. and F.T. Ulaby, "Feasibility of Monitoring Soil Moisture Using Active Microwave Remote Sensing," RSL Tech. Rept. 264-12, University of Kansas Center for Research, Inc., Lawrence, Kansas, 1977.

Batlivala, P.P. and F.T. Ulaby, "Estimation of Soil Moisture with Radar," Proc. Eleventh International Symposium on Remote Sensing of Environment, April 25-20, 1977, Ann Arbor, Michigan.

Blinn, J.C., and J.G. Quade, "Microwave Properties of Geological Materials: Studies of Penetration Depth and Moisture Effects," 4th Annual Earth Resource Program Review, NASA Johnson Space Center, Houston, Texas, January 17-21, 1972.

Burke, W.J., and J.F. Paris, "A Radiative Transfer Model for Microwave Emission from Bare Agricultural Soils," NASA Technical Memorandum TM X-58166, NASA Johnson Space Center, Houston, Texas, 1975.

Cihlar, J. and F.T. Ulaby, "Dielectric Properties of Soils as a Function of Moisture Content," RSL Tech. Rept. 177-47, University of Kansas Center for Research, Inc., Lawrence, Kansas, 1974.

Dickey, F.M., C. King, J.C. Holtzman and R.K. Moore. "Moisture Dependency of Radar Backscatter from Irrigated and Non-Irrigated Fields at 400 MHz and 13.3 GHz," IEEE Trans. on Geosci. Elect., v. GE-12, n. 1, pp. 19-22, 1974.

Eagleman, J.R., "Detection of Soil Moisture and Snow Characteristics from Skylab," Final Report, Tech. Rept. 239-23, University of Kansas Center for Research, Inc., Lawrence, Kansas, 1975.

Eagleman, J.R., and W.C. Lin, "Remote Sensing of Soil Moisture by a 21 cm Passive Radiometer," Journal of Geophysical Research, 81, 3660-3666, 1976.

Hipp, J.E., Soil electromagnetic parameters as a function of frequency, soil density, and soil moisture, Proceedings of the IEEE, 62, 98-103, 1974.

Hoekstra, P., and A. Delaney, Dielectric properties of soils at UHF and microwave frequencies, Journal of Geophysical Research, 79, 1699-1708, 1974.

Leschanskii, Y.I., G.N. Lebedeva, and V.D. Schumilin, Electrical parameters of sandy and loamy soils in the range of centimeter, decimeter and meter wavelengths, Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, 14, 562-569, 1971.

Lundien, J.R., Terrain analysis by electromagnetic means, Technical Report 3-693, Report 5, U.S. Army Waterways Experiment Station, Vicksburg, Miss., 1971.

McFarland, M.J., and B.J. Blanchard, Temporal correlation of antecedent precipitation with Nimbus 5 ESMR brightness temperatures, 2nd Hydrometeorology conference, Toronto, Canada, October 1977.

McFarland, M.J., The correlation of Skylab L-band brightness temperatures with antecedent precipitation, Proceedings of the Conference on Hydrometeorology, Fort Worth, Texas, April 1976.

Meneely, J.M., Application of the electrically scanning microwave radiometer (ESMR) to classification of the moisture condition of the ground, Earth Satellite Corporation, Final Report, Contract NAS5-22328, March 1977.

Newton, R.W., S.L. Lee, J.W. Rouse, and J.F. Paris, On the feasibility of remote monitoring of soil moisture with microwave sensors, 9th International Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, Mich., April 1974.

Newton, R.W. and E.A. Tesch, Joint Soil Moisture Experiment: Ground-based measurements at Texas A&M University, July 13-25, 1975, Technical Report RSC-71, Remote Sensing Center, Texas A&M University, College Station, Texas, 1976.

Newton, R.W., Microwave remote sensing and its application to soil moisture detection, Technical Report RSC-81, Remote Sensing Center Texas A&M University, College Station, Texas, 1976.

Njoku, E.G., and J.A. Kong, Theory for passive microwave remote sensing of near-surface soil moisture, Journal of Geophysical Research, 82, 3108-3118, 1977.

Poe, G., and A.T. Edgerton, Determination of soil moisture content using microwave radiometry, Final Report, 1684FR-1 DOC contract 0-35239, Aerojet General Corp., El Monte, Calif., 1971.

Schmugge, T.J., P. Gloersen, T. Wilheit, and F. Geiger, Remote sensing of soil moisture with microwave radiometers, Journal of Geophysical Research, 79, 317-323, 1974.

Schmugge, T.J., T. Wilheit, W. Webster, and P. Gloersen, Remote sensing of soil moisture with microwave radiometers II, NASA Technical Note TN D-8321, 1976.

Schmugge, T.J., J.M. Meneely, A. Rango, and R. Neff, Satellite Microwave observations of soil moisture variations, Water Resources Bulletin, 13, 265, 1977.

Schmugge, T.J., Remote sensing of surface soil moisture, 2nd Hydrometeorology Conference, Toronto, Canada, October 1977.

Ulaby, F.T., "Radar Measurement of Soil Moisture Content," IEEE Trans. on Antennas and Propagation, v. AP-22, pp. 257-265, 1974.

Ulaby, F.T., J. Cihlar and R.K. Moore, "Active Microwave Measurements of Soil Water Content," Remote Sensing of Environment, v. 3, pp. 185-203, 1974.

Ulaby, F.T., P.P. Batlivala, J. Cihlar and T. Schmugge, "Microwave Remote Sensing of Soil Moisture," Proc. of the Earth Resources Survey Symposium, June 8-13, 1975, Houston, Texas.

Ulaby, F.T. and P.P. Batlivala, "Optimum Radar Parameters for Mapping Soil Moisture," IEEE Trans. on Geosci. Elect., v. GE-14, n. 2, pp. 81-93, 1976.

Ulaby, F.T. and M.C. Dobson, "Analysis of the Active Microwave Response to Soil Moisture, Part I: Bare Ground," RSL Tech. Rept. 264-18, University of Kansas Center for Research, Inc., Lawrence, Kansas, 1977.

Ulaby, F.T., G.A. Bradley, M.C. Dobson and J.E. Bare, "Analysis of the Active Microwave Response to Soil Moisture, Part II: Vegetation-Covered Ground," RSL Tech. Rept. 264-19, University of Kansas Center for Research, Inc., Lawrence, Kansas, 1977.

Wiebe, M.L., Laboratory measurements of the complex dielectric constant of soils, Technical Report RSC-23, Texas A&M University, College Station, Texas, 1971.

Wilheit, T.T., Radiative transfer in a plane stratified dielectric, NASA Technical Memorandum TMX-71051, 1975, IEEE Trans. on Geosci. Elect., v. GE-16, n. 2, pp. 138-143, 1978.

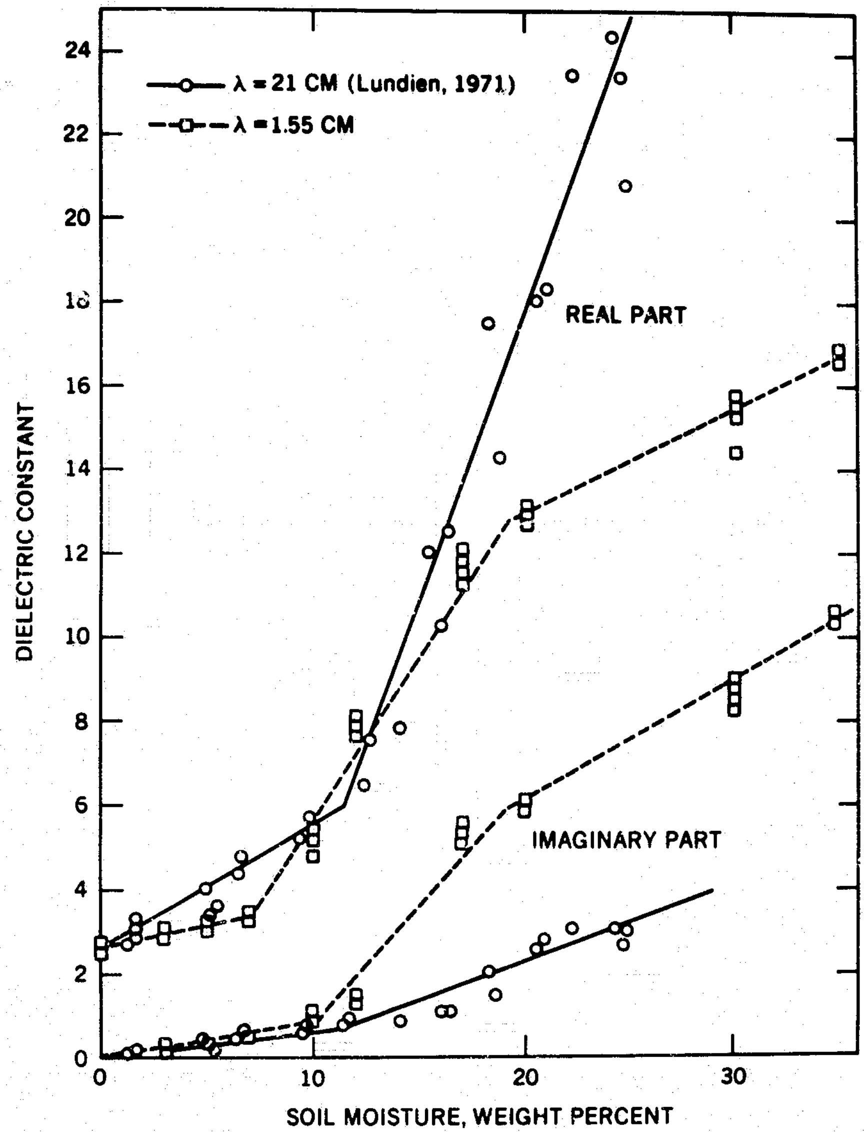

Fig. 5-1. Dependence of the soil's dielectric constant on its moisture content.

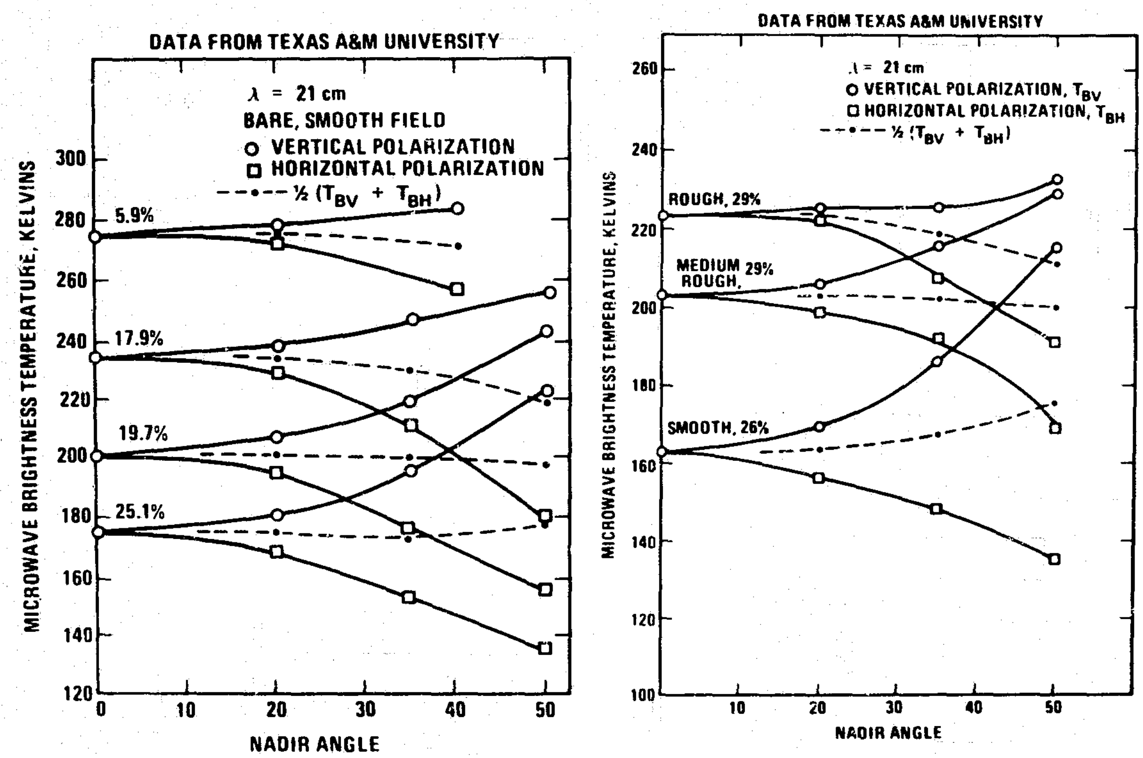

Fig. 5-2. Results from field measurements performed at Texas A & M University: (a) T_B versus angle for different moisture levels; (b) T_B versus angle for different surface roughness at about the same moisture level (Newton, 1976).

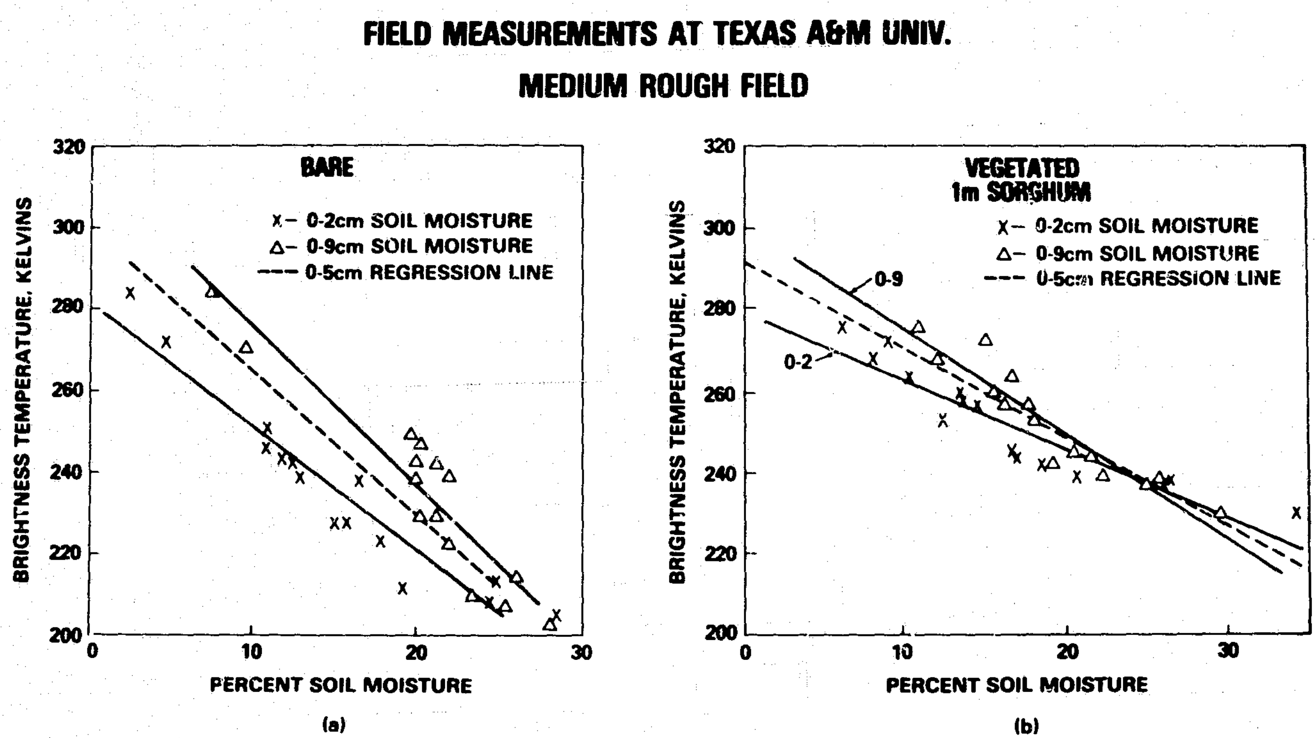

Fig. 5-3. Field measurements of T_B versus soil moisture in different layers for the medium rough field: (a) bare; (b) vegetated, 1 m of sorghum (Newton, 1976).

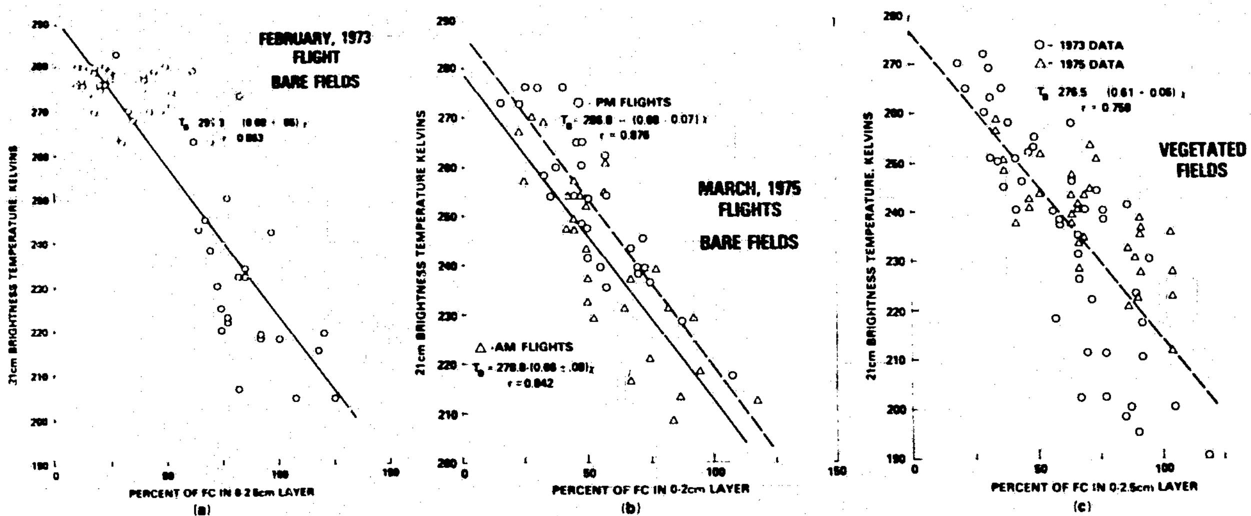

Fig. 5-4. Aircraft observations of T_B over agricultural fields around Phoenix, Arizona: (a) bare field results from 1973 flight; (b) bare field results from 1975 flights; (c) vegetated field results from both years.

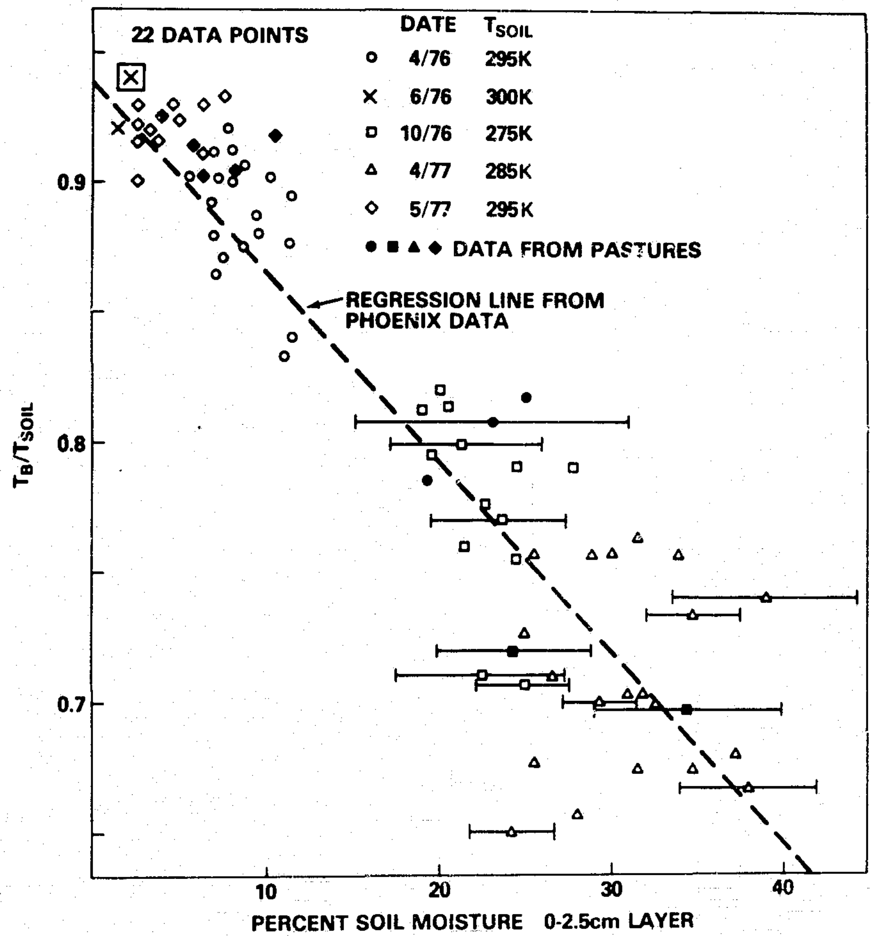

Fig. 5-5. Aircraft observations of T_B during 1976 and 1977 flights over agricultural fields in Hand County, South Dakota.

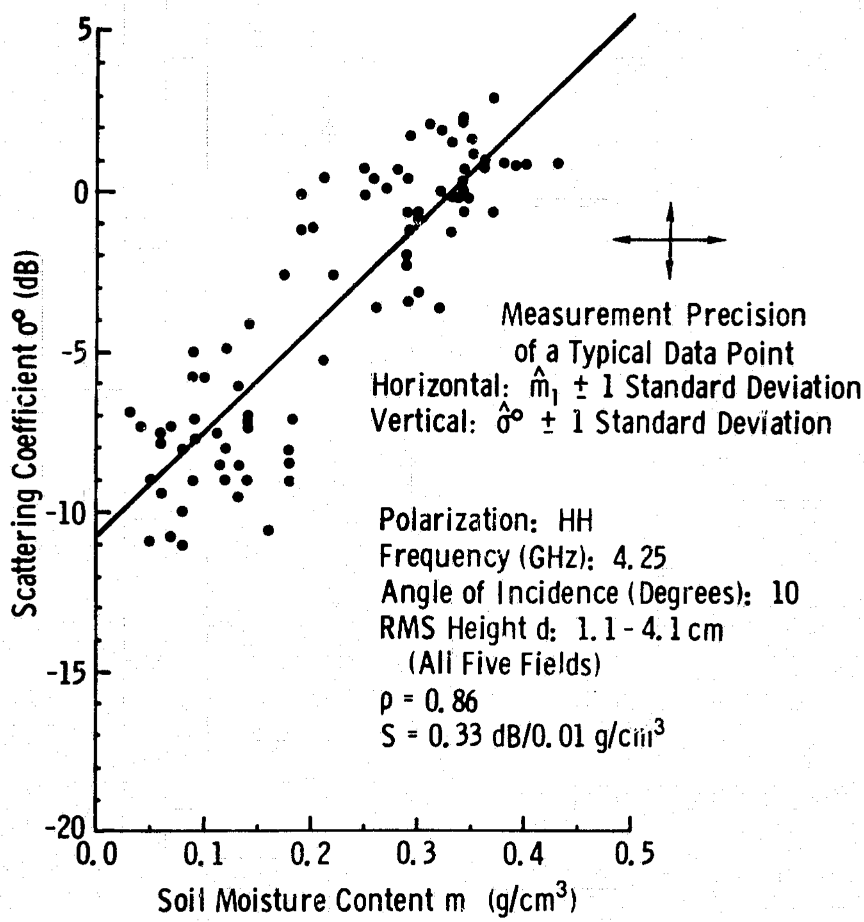

Fig. 5-6. Scattering coefficient as a function of moisture content in top cm for 84 data sets (data from all five fields were included).

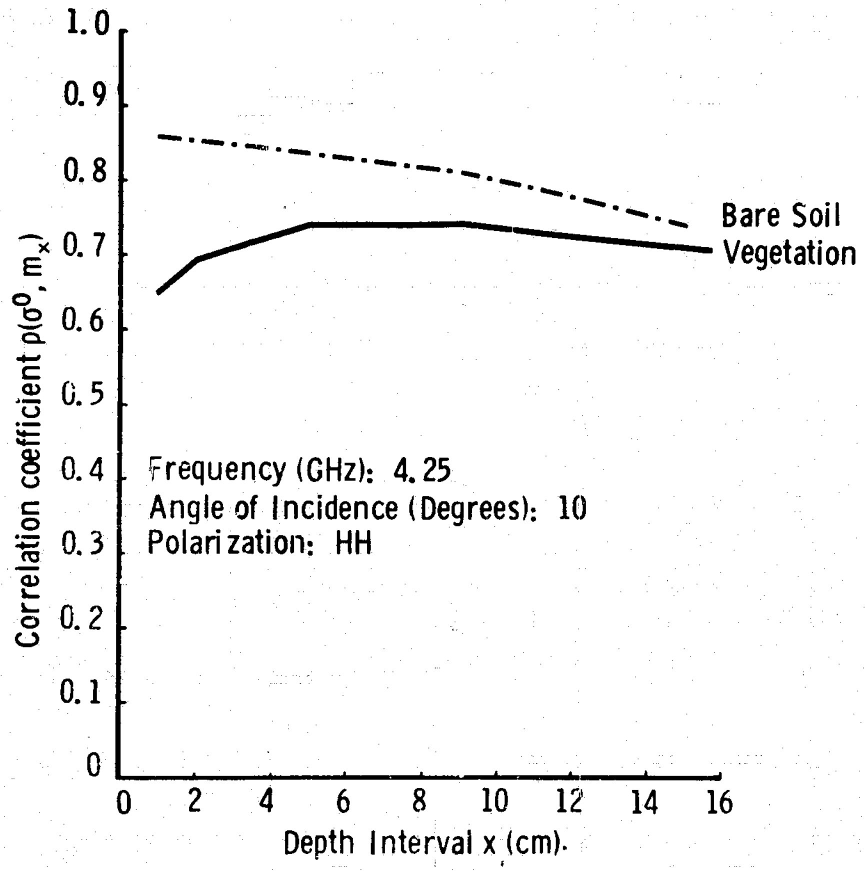

Fig. 5-7. Correlation coefficient of $\sigma°$ and m_x for bare soil and vegetation covered soil. (m_x is moisture in top x cm of the soil).

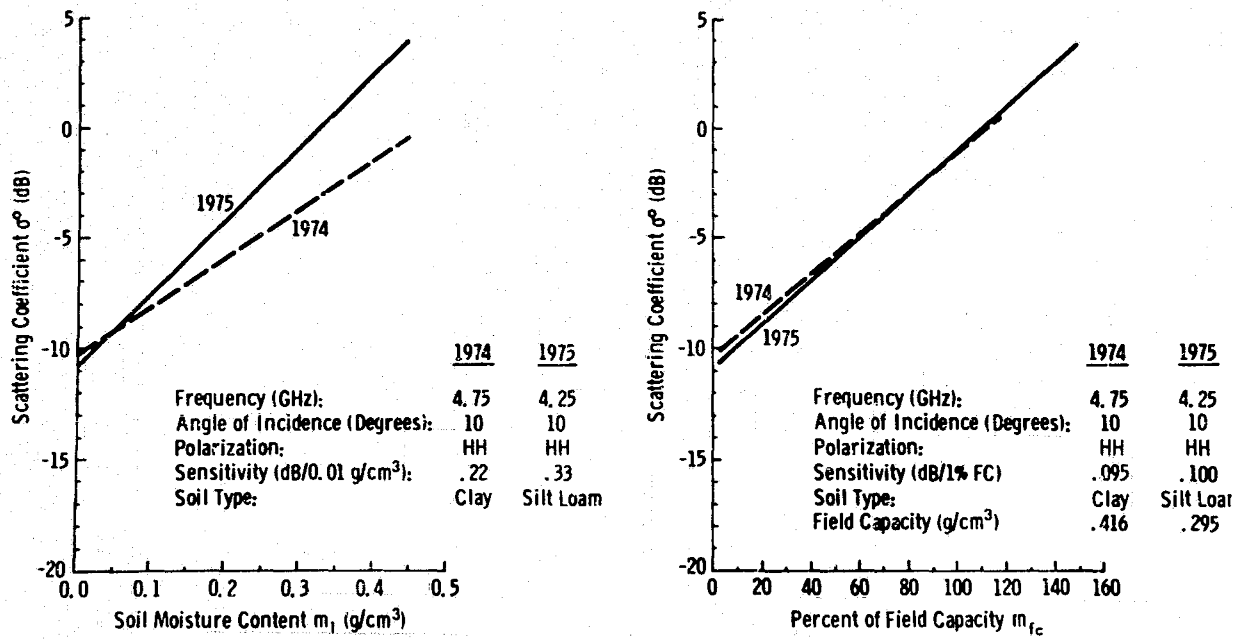

Fig. 5-8. Comparison of regression results of 1974 and 1975 experiments with moisture expressed: (a) volumetrically and (b) as percent of field capacity.

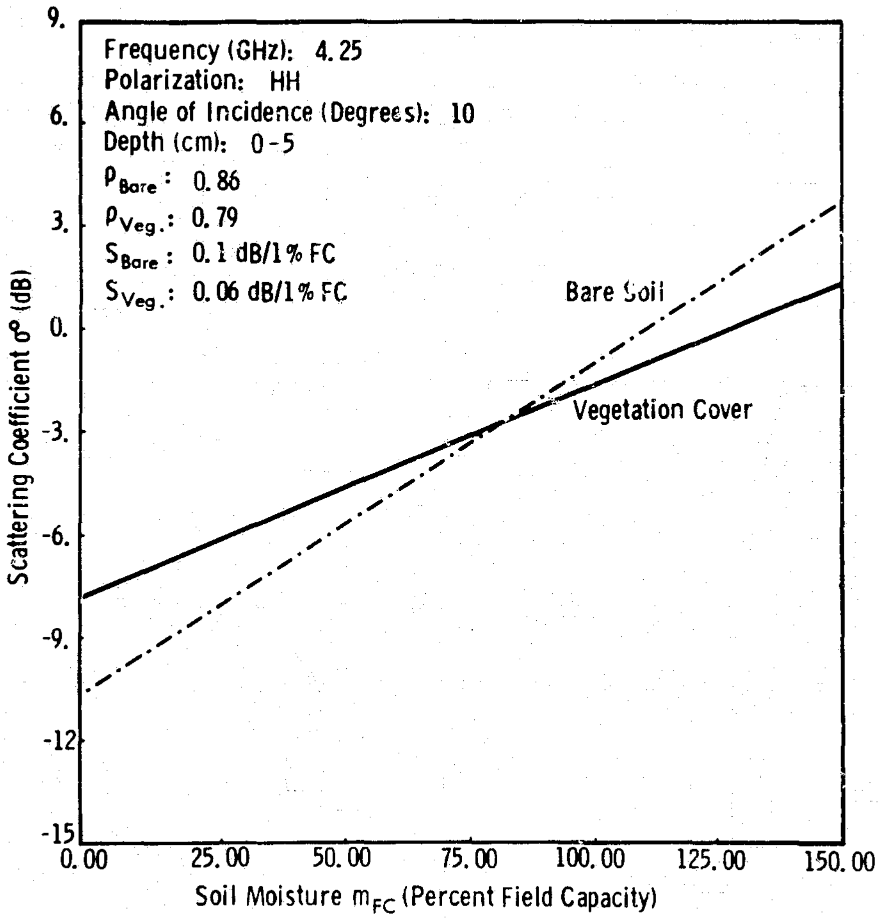

Fig. 5-9. Comparison of bare soil and vegetation cover σ^o dependence on soil moisture.

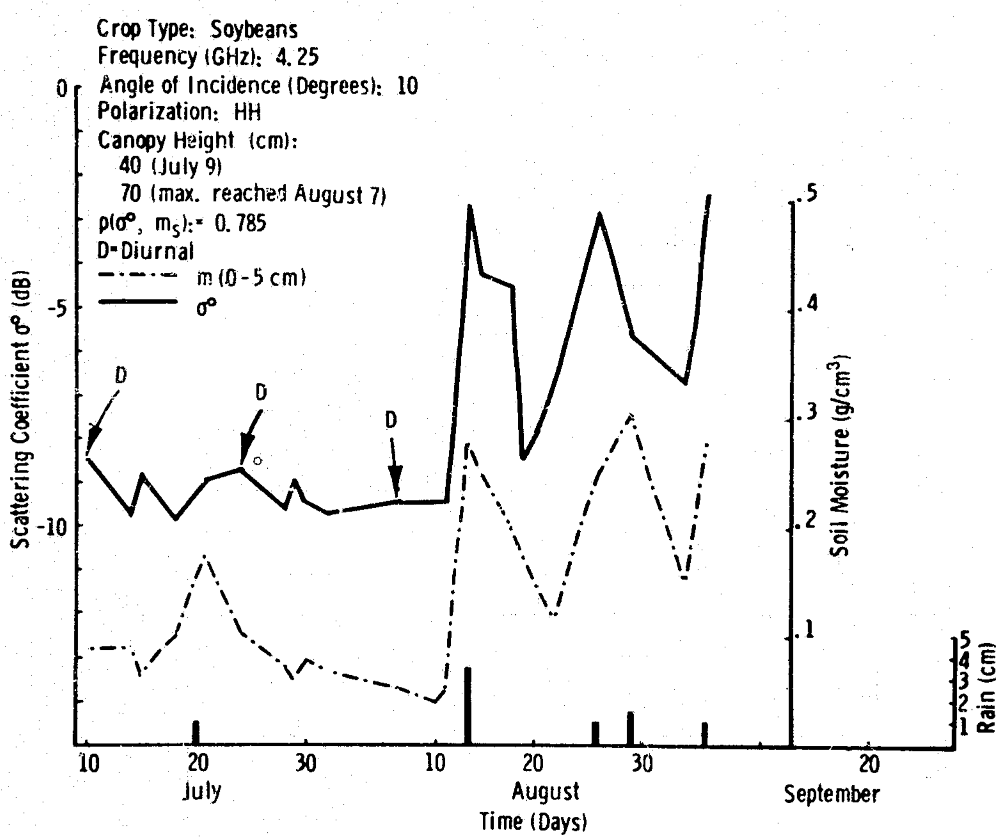

Fig. 5-10. Radar response to soil moisture through soybean canopy (1975).

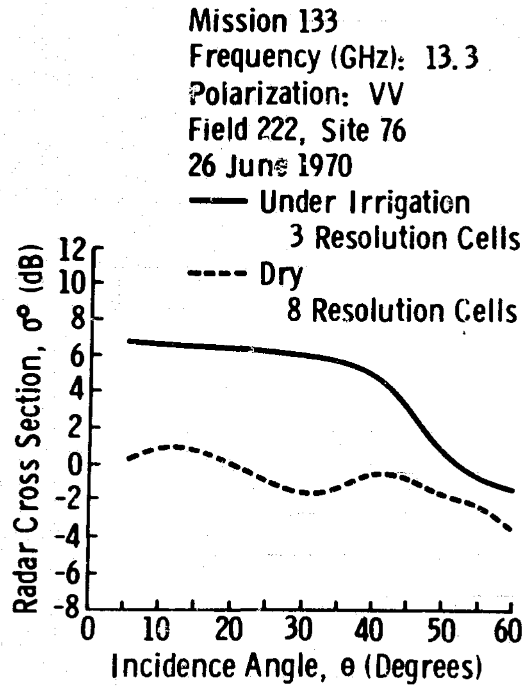

Fig. 5-11a. Scattering coefficient as a function of incidence angle for irrigated and non-irrigated sections of a corn field. From Dickey et al. (1974).

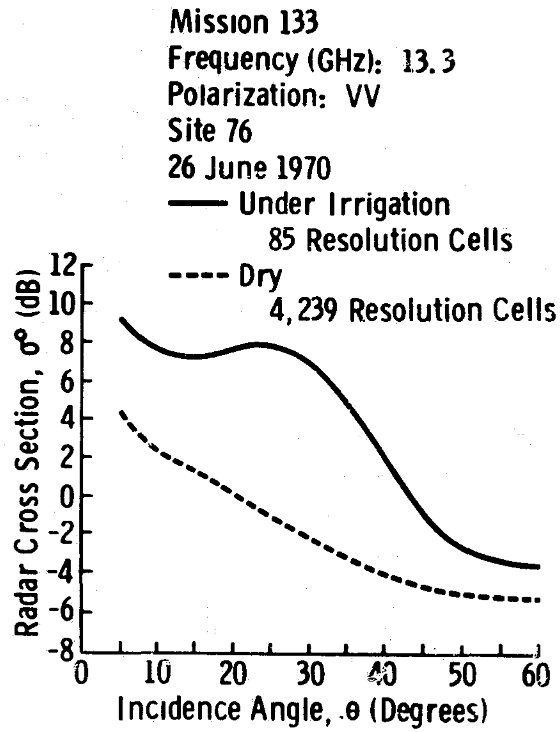

Fig. 5-11b. Average scattering coefficient as a function of incidence angle for irrigated and dry terrain. From Dickey et al. (1974).

CHAPTER 6

PROCEEDINGS OF SUMMARY AND RECOMMENDATIONS SESSION

A. OPENING REMARKS

D.G. Moore

Discussions by recognized discipline scientists and information users have shown the diversity of opinion on the actual use of soil moisture information and the approaches which may lead to successful remote sensing measurements of soil moisture. As with other facets of nature, soil moisture has varying definitions and information needs depending on one's perspective of discipline and defined use. With these differences of need and definition predominating, our task as a summary panel is difficult. If microwave can be used to detect and quantify moisture in the first few centimeters of soil depth, how can the agronomist satisfy his information needs when the crop root extracts moisture from many fold of this depth and the plant views moisture as a tensiometric quantity and not a gravimetric or volumetric quantity. If the microclimate of a plant canopy yields information by thermal infrared sensing concerning moisture stress, how can the hydrologist relate to the moisture of the near surface of the soil which will affect infiltration rates.

One approach to understanding nature is to develop and evaluate simulation and prediction models. When applying these models for predictive purposes certain parameters must be measured in the field. When the parameter is not well understood or is near-impossible to measure the terms are grouped as a coefficient. The importance of soil moisture has been well illustrated in the models presented at this conference. Even though the information is spatially difficult to acquire, for even a small agricultural field as has been illustrated, the specific term is retained in these models because of its importance for successful and accurate implementation. This feature in itself provides the incentive to develop methods which can sequentially and accurately assess soil moisture synoptically.

Today, we have requested a distinguished panel to provide summaries of the past two days' activities and make recommendations with interaction from all workshop participants considering 1) what is the "state of the art" for using and acquiring the soil moisture information, 2) does the need exist for advancing this technology, and 3) what can NASA and other interested agencies do to advance the technology. The group chairmen will briefly summarize their observations to date for the benefit of the conference participants who were unable to attend their respective sessions.

B. WORK GROUP SUMMARIES

Summary of Applications Group (C.J. Johannsen)

In my remarks, I will focus on agricultural aspects of soil moisture needs which will include forestry and rangeland. It was difficult for our committee to find a real direct user of soil moisture information because we are not currently supplying soil moisture information. We found many examples of indirect uses of soil moisture information and therefore we have identified many potential rather than present users.

Indirect use of soil moisture information begins with the planning functions. The amount of inferred soil moisture determines planning for field operations, transportation, storage, supplies, etc. Yield and production predictions utilize inferred soil moisture information and estimates of anticipated rainfall. Insect and disease epidemiology utilizes soil moisture estimates and prediction of future moisture and temperature conditions.

Many users utilize rainfall information to infer soil moisture. This is extremely difficult because of a number of factors such as rainfall intensity which influences infiltration, type of soil which determines how much is held and available to vegetation, temperature conditions which influence vegetative growth and evaporation, and many other complex factors.

There are several classification systems which use soil moisture as one of its criteria. In the National Cooperative Soil Survey Program, soil moisture regimes are defined in terms of soil moisture in the soil region that supports plant roots. Another classification system which utilizes soil moisture information is the Wetland Classification System recently initiated by the U.S. Fish and Wildlife Service.

The needs for soil moisture information in foreign countries is becoming more significant. Data bases of soil information are being developed for many countries but it is found that soil moisture would greatly assist in planning efforts, demonstration projects, initiation of new crops, etc.

It was difficult for all users to clearly define their data needs in terms of accuracy, resolution and frequency. The committee made a first attempt and showed some ranges in their estimates because the needs of different users will vary. In most cases, it was found that initially the timeliness of an excess or a shortage of soil moisture information is more important than accuracy. The alert of a possible soil moisture condition begins an initiation of a series of events to counteract or complement that condition.

Once the initial information has been released, efforts should be made to refine the data and improve the accuracy of the information. Many users are also concerned about the depth of measurement of soil moisture. Most would like to know the amount of soil moisture that is held within the root zone of approximately two meters.

Communication will be a very important factor in the success of utilization of soil moisture information. This workshop has brought together people from many different disciplines who view soil moisture from equipment development, measurements, analysis, and dissemination aspects. These different areas need to communicate with one another to provide a product that the user can use in his daily operations.

Summary of Reflectance and Thermal IR Group (R.D. Jackson)

Yesterday we discussed the use of Landsat imagery to delineate perched water tables in California. This study has progressed to the point that it could go operational. We also discussed the use of reflected radiation to delineate stresses in crops. It became apparent that there is a problem in delineating a water stress from biological stress in crops. In other words, more research is needed to identify and separate the various stresses that might be detected by a remote sensor.

We discussed the use of reflected radiation to infer soil moisture in bare soils, and showed what everybody knew all along; that with reflected radiation you can only get an estimate of the water content near the surface. It is essentially yes or no type information, "yes it's wet, or no it's dry." One might tend to throw that type of information away because of its apparent limited usefulness. However, that type of information, in conjunction with other remotely measured data or simulation models, could be very useful.

We discussed the use of thermal infrared to estimate water content. With thermal infrared we have experimentally demonstrated that we can infer water contents to approximately 5 cm. Five centimeters may be of little value to those who need to know the water content of the root zones. Others, however, who may be interested in pest management would say that depth is sufficient because that's where insects lay their eggs. Soil moisture maps of large areas could aid in locating where insects are developing. It is easier to control the insects early in the cycle before they spread and devastate crop lands. It is the specific needs of the application that will decide whether the water content in the top 5 cm is sufficient.

We discussed some research that indicates that we may be able to use thermal IR to measure crop canopy temperatures, and thus use plants as an indicator of the water content with depth. In this area we really do not need to know the water content per se. We need to know whether, and to what degree, the plant is stressed at that particular time. However, we would like to know how much water is stored in the root zone for determining future water availability. The thermal IR data at present are largely ground based with a few measurements from aircraft. We have no data from satellites as yet, except for very limited Skylab observations, but we hope to obtain some with the HCMM. The use of thermal IR for estimating crop water stress or crop condition, has applications, or at least possibilities, for irrigation scheduling and yield predictions. In the rain-fed agricultural areas thermal IR could assist in assessing crop "health" after a period of water stress for estimating the yield. We cannot do much about water stress when we depend on rainfall for water. In the irrigated areas of the west the detection of the onset of stress could be used to help schedule irrigations.

We discussed agrometeorological models, in particular the Kansas State model that uses Landsat imagery to estimate leaf area index, evapotranspiration, soil moisture, and yield. This approach looks promising. JPL and NASA efforts to develop detailed soil moisture models are making good progress. The group generally agreed that one way of monitoring soil moisture on a daily basis would be to use a model that would run on meteorological inputs and could be frequently "fine tuned" using remote sensing inputs.

An obvious limitation of both the reflected and thermal techniques is the presence of clouds. Cloud cover often precludes measurements from aircraft and satellites. In addition to the cloud cover problem is that of attenuation of radiation by water vapor in the atmosphere. There are, however, some techniques that allow one to account for this problem. On the ground there is the problem of topography. Different slopes and aspects can have a wide range of water contents. With similar slopes and different aspects, a considerably different temperature might be measured while the soil water content is essentially the same.

What are other problems that need more work? We believe that we can do reasonably well in estimating water content of bare soils, and if we have a complete crop canopy cover we can also make some reasonable estimate of plant "health". It is the in-between area of intermediate crop cover that causes problems that have not yet been solved. Hopefully, we can devise some way using a combination of techniques, perhaps reflected and thermal IR along with microwave.

For many applications in agriculture, we need very frequent coverage. Seven to ten days has been suggested. In many cases that is sufficient. In other cases we may have to have coverage at least every three days. I think we can probably get by without every-day coverage, although some of our research is geared to acquiring ground data on a daily basis. I mentioned the fact that there are several things that can cause stress in plants. We could easily infer the wrong cause, especially if we draw conclusions from only one measurement. Repetitive measurements provide considerably more information. For example, if we monitored a field with thermal IR and discovered a hot spot in the middle of the field and previous measurements indicated that it had been irrigated a few days ago, one would suspect a disease or insect stress. Repetitive measurements allow us to deduce a probable cause by elimination.

The optimum time for evaluating soil moisture using thermal IR is between 12:00 noon and 2:00 p.m. when the largest difference between soil or vegetation surface temperature and air temperature occurs. Also during this period differences with time are small, so a modest period of time exists to make measurements. If measurements are made near the Landsat overpass time the temperatures are rapidly changing.

This workshop has been concerned with identifying criteria that NASA can use to design a satellite to monitor soil moisture. I feel quite strongly that we in agriculture still have a lot of work to do to develop principles that can be used in interpreting remote measurements of soil and plant surfaces. It is not just up to NASA to build a better satellite; in agriculture, we must do considerably more research.

Question (L. Walter)

It appears that there is less noise in remote sensing systems sometimes than is apparent in ground verification of them. Is that right, first of all; and secondly, have you discussed the availability of improved soil moisture sensors for ground use?

Response (R.D. Jackson)

The answer is yes to the first, and to the second, no, we did not discuss it to any great extent. It is something that is extremely important. How do you ever verify remote sensing of soil moisture by going out and taking small soil samples? How many samples in a 40-acre field do you need? Bruce Blanchard came to Phoenix, worked hard on this problem, and we are still not sure what the answer is. It is a terrific problem. How do you make sure that what you are measuring from an aircraft or satellite matches what you do on the ground? When comparing ground data with aircraft, which one is correct? Each individual sample that we take on the ground may be a good measurement, but is it representative of a spot ten feet away? Somehow we need to come up with a better verification program.

Comment (E.T. Kanemasu)

In regard to your comment concerning verification, measurement accuracy requirements depend on the soil moisture application. In some cases, for example watershed hydrology, you only need three levels of soil moisture. In irrigation scheduling, there is a wide range of water contents in which plant growth is unaffected. It is the critical level that must be detected. So I do not think it looks as bleak as perceived just because you cannot measure soil moisture of a large field.

Response (R.D. Jackson)

I agree with you. I think that what we are addressing here is a comparison of measurements. If you have a 40 or 80-acre field and you had a one-shot measurement with either microwave or thermal IR, and had a number of field samples of soil water content integrated over that whole field, to what degree of accuracy could we say which is right and which is wrong? How many samples would we have to take on the ground to do that? I agree if you only need levels of high, medium or low for that sample we can do it. But some people after yesterday's microwave presentation were questioning the validity of data that has considerable scatter. What causes the scatter? Is the scatter due to the remote sensing measurement or the ground-based measurement? That is the question that must be answered.

Summary of Microwave and Gamma Radiation Group (T.J. Schmugge)

We have considered what we call the direct observations of soil moisture where a soil property such as emissivity or reflectivity is measured. The three approaches that we discussed were active microwave, passive microwave, and gamma radiation.

Ninety percent of the gamma radiation from the radioactive component in the soil comes from the surface 10 cm of the soil, so variations in the observed gamma ray count depend upon the moisture content in that surface 10 centimeters. The gamma radiation technique is based on the fact that if soil moisture content increases, the soil density increases, and more of the gamma radiation coming up from below is absorbed. To use the technique it is necessary to have a calibration point when the soil is dry, and fly over it at other stages of moisture to determine the relative moisture content.

The microwave approaches depend upon the fact that the dielectric properties of the soil affect the behavior or ability to transmit electromagnetic waves. This applies for both the active microwave and the passive microwave approaches. In the active microwave approach, a radar sensor transmits electromagnetic energy from the platform in the aircraft, spacecraft or tower, and the energy that is returned or backscattered into the sensor is measured. The backscattering depends upon the dielectric properties of the surface, namely moisture content; and the surface roughness characteristics. In the passive microwave approach, the thermal emission from the soil in the microwave wavelength is measured. In the thermal infrared approach, the emission is measured at the peak in the emitted energy spectrum. At microwave wavelengths radiation levels are much lower. Measurement at microwave wavelengths is possible because at these wavelengths we have a better ability to amplify the low power levels. What I would like to do now is give a brief review of the discussion that was presented yesterday and then comment concerning the relative attributes of the various techniques.

The basis for using the microwave approach is the fact that the dielectric properties of soils depend very strongly on the moisture content of the soil. Laboratory measurements of the dielectric constant at a short and at a longer wavelength for two clay loam soils have shown a bilinear behavior at both wavelengths, and the intersection of the two dielectric constant versus soil moisture lines has been shown to be a function of the soil texture. For active microwave, Dr. Ulaby and his group at the University of Kansas observed the radar backscatter from soils to be a function of wavelength in the range from 30 to 3 cm. They looked at it as a function of angles from nadir out to 40 to 50° and considered five different fields with different surface roughness characteristics. They came to the conclusion that a radar operating at a frequency of 4 to 5 GHz and an angle of incidence of 10° gives the best correlation of measured backscatter with ground measurements of soil moisture independent of the surface conditions.

For the passive microwave, we have not looked at as wide a range of wavelengths but on the basis of several years of aircraft experiments with multiwavelength systems we have found that measurements at wavelengths on the order of 21 centimeters have correlated with ground measurements of soil moisture. In addition, some of the scatter in the variation of surface conditions, especially surface roughness, will affect the response, particularly in the wetter moisture conditions. For dry moisture conditions the effect of surface roughness is much less. I feel that with a radiometer operating at this wavelength we are able to respond to surface soil moisture variations for a wide range of surface conditions.

I would like to summarize the evaluation of the three approaches in terms of what I see as some of their pros and cons. From the gamma ray approach, Dr. Peck has pointed out that it is an approach that will be independent of soil temperature and surface roughness conditions. We are only looking at the gamma ray emission from the soil and how it is absorbed by the bulk soil materials above radiation sources. This approach has very poor spatial resolution; the data that he has shown for an aircraft flying at 500 feet covers approximately a quarter mile swath of land. Low altitudes are required because of atmospheric effects. The radiation coming from the atmosphere itself can overwhelm the radiation coming from the soil at much higher altitudes.

The microwave approaches have the obvious advantage of an all weather capability. The non-raining cloud situation does not interfere with the measurement. Even the raining clouds have minimal interference.

Active microwaves offer the possibility of high spatial resolution. Resolutions of 100 meters or better are possible with synthetic aperture radar techniques. Resolutions on the order of a kilometer are possible with real imaging radar. Another important factor in active microwave is that measurements are independent of the temperature. Surface roughness will be a noise factor and will limit the ultimate accuracy obtainable for inferring soil moisture. The strong dependence on look angle will limit the swath width. The proposed angular swath is of the order from 7 to 17° which from an orbiting system would limit the swath that can be covered with a single instrument. The dependence on look angle will require information on surface slope variations for the terrain that is being observed. A third problem is can we build an imaging radar that can be calibrated well enough to make the measurements that are necessary? This is something we ultimately will be able to do.

In the passive microwave case, the relative insensitivity to look angle indicates that passive microwave has the capability of obtaining wide swath information that will be insensitive to surface slope variations. Surface roughness and soil temperature will introduce noise. We indicated that we had some ideas on dealing with temperature effects, but we need more research on surface roughness. The coarse spatial resolution will limit the interpretation of the data when a 10 kilometer footprint covers a mixed scene on the ground. Antennas larger than 10 meters may be required.

I feel that these three approaches can make a determination of the surface moisture conditions, and it will be a question of how we can use that surface soil moisture information.

C. PANEL OBSERVATIONS AND RECOMMENDATIONS

A.A. Klingebiel

I represent users and perhaps can serve as a barometer in evaluating some of the information presented at this conference. A great deal of information has been presented during the past two days about soil moisture, its importance, and the various methods used to measure it. I have no profound conclusions to make, but I do have several observations I would like to leave with you.

There is need for recognition and use of soil maps and interpretations to provide a physical base for evaluating soil moisture. Very little evidence was presented that would indicate this information is used.

It is my opinion that we have the ability to develop a program that would provide soil moisture predictions, both excesses and deficits, that would be beneficial to farmers and to agribusiness. The information I have in mind would be provided to users for major kinds of soil within regions in states and would be given in a usable form perhaps on a weekly basis. It would help the farmer decide about planting and harvesting crops, kinds and amounts of crops to plant, use of fertilizers, herbicides and insecticides, hazards of flooding, depth to water table, and a number of other activities.

This program could start with a generalized soil map that would be interpreted to show water holding capacity and/or moisture supplying capacity of soils. General soil maps are available for whole counties and can be obtained and interpreted for various moisture classes. The new soil taxonomy as now used in the U.S. by the National Cooperative Soil Survey includes a classification for soil moisture. Copies of this classification including soil moisture have been prepared for the whole world and are now available. Such maps can be prepared for individual counties, for states or for other areas. By knowing the kind of soil and the water holding capacity of that soil you have a starting point of reference from which moisture condition of the soil can be determined periodically during the growing season.

Some kinds of soil have two to ten times the capacity of others to hold moisture. Farmers can be advised of the soil moisture available to plants by kinds of soil. Methodology on how to use this system can be developed in a reasonably short time by scientists knowledgeable about these matters. Pilot studies could be developed to work out the "bugs" and to improve the procedures.

We need to explore more fully the use of data from meteorological satellites in combination with Landsat, aerial flights and ground data. There appears to be a need for closer cooperation and exchange of data and ideas between agencies utilizing these different satellites. I heard very little about the actual user of the weather satellites, but was led to believe much could be gained from them. Perhaps we need a stationary satellite with the kind of equipment we could use in agriculture.

Much of the money spent on remote sensing research seems to be spent on hardware with little left over to carry out experiments. If remote sensing research is to survive someone needs to address applications research where this system is presently available to use the information.

Many participants indicated that methods for gathering ground data lag behind the satellite technology. Farmers are "weather men" in their own right. They observe the moisture of the soil and commonly have a rain gauge of some kind to measure precipitation. A system now being used in Delaware and Maryland allows for farmers to supply these kinds of information to be placed in a computer. This system allows for a method of recording ground data at a minimum cost.

More publicity needs to be given to practical results obtained in the field of remote sensing. Some programs need to be made operational even if they provide only broad guidelines.

When one goes into a developing country to advise on potential for producing food and fiber there is an immediate need to have information about the soils, their ability to hold moisture and the rainfall distribution and amount. Again with a soil map and knowledge about the climate one can put these data together and develop a program that will provide information on the potential for producing food and fiber. We have the leaders here in remote sensing at this conference, that have the ability to develop a program that would be extremely useful to anyone working on the problem of resource development and use.

V.V. Salomonson

I am going to be speaking to you from the point of view of an advocate of water resources management and hydrology research. I believe there is a need both within NASA and outside NASA to advocate research in this particular area. In addition there is a growing need to manage water resources over larger areas and as that need grows, it becomes more compatible with the inherent capabilities of satellites. This emphasis and my proposals are generally associated with large region macroscale hydrology, large region agriculture, and regional and global climate.

Remote sensing from aircraft and spacecraft should be considered as complementary and ancillary data to conventional systems. Conventional systems would serve as benchmarks, references or check-points. I think furthermore that multiwavelength sensors covering major portions of the spectrum will always be necessary. Anything we propose here should be regarded as complementary to existing systems like the Earth Resources Satellite Systems and meteorological environmental satellite systems. Finally there is a need to do modeling studies and data analysis studies. There is also quite clearly a need to provide better means of getting corroborating ground observations.

With reference to Dr. Meredith's questions, he asks whether a developmental program is justified. If by that is meant a system of programs that will provide improved soil moisture information, I think the answer is yes. The comments of the workshop have indicated that the importance of soil moisture ranges from at least significant to very important.

What should be the development of priorities? Among the candidates are climate needs, water resources, management needs, and agricultural needs. I advocate water resource management because a knowledge of the hydrologic cycle and improved information concerning water resources are fundamental both to climate and agriculture.

Should the development be research oriented or operationally oriented? It is my view that there are too many questions at the present time about depth of penetration, the applicability of repetitive measurements, and the effect of vegetation to indicate that we can say an operational program exists. However, there are enough research results to justify an aggressive research program.

What observational capabilities are needed and what kind of a research program should be developed? Referring to Table 6-1, I again emphasize that there is a need to develop models. In my opinion our first emphasis should be on developing large-region, climate-oriented models that include soil moisture budgets and evapotranspiration models. In time, the second emphasis should be on water resource models, and the final and ultimate emphasis should be on crop yield or multicrop models. The need throughout to do data analysis and interpretation technique development is very much emphasized. On the top of the table (Table 6-1) is indicated that earth resource satellites which have generally higher resolutions and relatively infrequent coverage should undergo continued development and focus on measuring fields, land use boundaries, flooded areas, etc. They should be complemented by satellite systems that can provide dynamic, highly repetitive, large area coverage. As a basic premise I note that it takes five, plus or minus two, years to get any sort of spacecraft system into orbit. In the mean time, a research program starting out with a ground and aircraft effort should be executed between 1979 and 1981. These efforts should take place at three to five dissimilar sites including different kinds of atmospheric regimes, soils, etc. It

Table 6-1. SOIL MOISTURE WORKSHOP
JANUARY 17-19, 1978
(V. SALOMONSON/GSFC)
SYSTEMS/RESEARCH PLAN OUTLINE (1/19/78 PANEL INPUT)

ITEM	1979 – 1981 – 1983 – 1985 – 1987 – 1989 – 1991	Remarks
Earth Resources Satellites Landsat C, D, E, etc.	C → D → E, etc. →	Continually improving, oriented to mensuration, boundaries, land use, etc.
Ground Based efforts, existing aircraft, effects of vegetation, depth, etc. 3 - 5 sites	→ research	Use gamma radiation for ground truth Develop hand-held radiometers for plant stress, soil moisture, ground truth, etc.
Mid-range, improved aircraft sensors 3 - 5 sites	spacecraft simulation (research) → aircraft underflights →	Develop improved aircraft sensors for research support and special applications tests
Initial spacecraft, -climate-oriented test	research → operational →	Visible/IR, AVHRR/HCMM; 1km-500m; Microwave/Multifrequency, passive, 4 bands; 1 week delivery; 1 PM equator crossing; also polar region, sea-ice, snow cover and soil moisture
2nd Generation spacecraft, water resources-oriented test	research → operational →	Visible/IR, advanced AVHRR; 500-250m; Microwave, 4 bands; 1 km; 3 day data delivery do global, met/ag support
3rd Generation spacecraft, agriculturally - oriented test	research → operational →	Visible/IR; 250m; daily coverage; 250-500m microwave, multifrequency; Geosynchronous Landsat capability or Severe Storms capability Emphasize CRD, state, regional coverage, hourly delivery in special situations
Model Development	climate models, soil moisture budget and evapotranspiration with remote sensing → distributed parameters remote sensing-oriented water resources models → crop yield, multi-crop models →	
Data Analysis/Interpretation Technique/Development	Emphasize Throughout/Use Metsat data also	

is also suggested that this program should consider using gamma radiation flights as ground truth. Also, as a spinoff of this effort, we might be receptive to the development of some handheld devices that could be used as ground truth to cover larger areas more rapidly.

The second stage of this research program would focus on an improved aircraft sensor program taking place somewhere in the 1981 to 1983 period. It again would cover three to five sites and continue refining our knowledge about vegetation effects, penetration depths and the importance of repetitive coverage. In this stage of the total program, the emphasis should be on spacecraft simulation wherein an effort would be made to cover three to five sites every three days to see what type of advantage repetitive coverage gives in terms of incremental improvement in model performance and soil moisture specification.

The third stage would involve an initial research spacecraft test. It would emphasize climate initially because climatic requirements in time and space are the least exacting. This stage would take place in the 1983 to 1987 period. The relevant spacecraft system would include visible and infrared sensors that resemble some combination or approximation of the capabilities of TIROS-N or HCMM. The spatial resolution would be 500 meters to one kilometer. The orbit would provide daily coverage in the visible, near infrared and thermal IR associated with a 1:00 p.m. equator crossing time on the daylight, descending node. This would mean 1:30 to 2:00 p.m. observations in the mid latitudes and observations near midnight on the night pass. A four frequency passive microwave system providing three day repeat coverage at 10 km spatial resolution should also be included. A point should be made that if this system were on a sun-synchronous, polar orbiting spacecraft, it would also be applicable to research in snow moisture, polar region studies, sea ice studies and many other topics.

The second generation spacecraft system would be oriented toward water resources. It would have a visible and IR system that would provide 5 meter spatial resolution and daily coverage. Again it should have a HCMM orbit, with three day data delivery and a microwave (passive or active not specified) system with one kilometer spatial resolution. It should emphasize the soil moisture watersheds larger than 1,000 kilometers. In the meantime the table (Table 6-1) indicates that quasi-operational application of the data from the first data generation system should be occurring.

As a final phase that includes a more speculative, advanced system, a program would be suggested to address the more difficult requirements of agriculture, such as high resolution estimates of moisture. This system would involve a visible and IR system providing 250 meter resolution. A multi-frequency microwave system would be operated with 100 meter resolution covering large areas. Data delivery in one day for selective research situations would be provided. It might all be backed up with a geosynchronous satellite designed to study severe storms, precipitation, hail, or other severe storms subjects.

This has been an outline of what I believe to be a useful, aggressive, and responsive water resources program. I think it is important to embark on this kind of program as soon as possible. I firmly believe that if we establish this kind of a program, it will be of considerable benefit not only to those of us involved in it personally, but to organizations, individuals and governments throughout the world.

D.S. Simonett

I am much in sympathy with the points just made by Vince Salomonson. The first problem we should look at is the input side of the soil moisture problem, namely the amount of rain falling in a given location. The spatial network of rain gauges to sample that rain is inadequate. It is suitable only for climatological measurements. It is completely inadequate for detailed measurements and for driving monitoring systems on a daily or 3-day basis. To upgrade our understanding of soil moisture we cannot rely exclusively on rain gauges.

Rainfall is both spatially and temporally a discontinuous phenomenon. This requires a precipitation intensity model, cloud type model and meteorological satellite interpretation data plus rain gauges. We have meteorological satellites at present which look from 2 to 4 times a day and others which look about every 30 minutes. Both are needed to interpret the life history of stochastic type rainfall from cumuliform precipitation. Most of our soil moisture problems occur in summer. The bulk of our rainfall in summer is not frontal, it is essentially stochastic arising from the thermal load on the ground and/or from small frontal perturbations added to give a highly time/space varying rainfall. Also, during drought conditions, that stochastic process is exacerbated by a more than ordinarily spotty precipitation plus the fact that the environment (through variations in soil type, slope, etc.) begins to operate on that rainfall and spatially disjunct soil moisture distributions become more important. Consequently, I cannot agree, in general, with the proposition that we can meaningfully employ only coarse spatial averaging of a highly disjunct, discontinuous, time and space varying distribution, for model inputs, anymore than I can accept that point-sample rain gauges every 20 to 50 miles or so provide a meaningful sample of daily rainfall - though they probably do for monthly rainfall.

For example, I am not in sympathy with the view that 15 to 50 kilometer resolution passive microwave observations could possibly be acceptable by themselves. In such systems, single observations fit a running average to a very large area. Many different spatial distributions of soil and surface moisture within the resolution cell could give the same average value, with different hydrologic or crop-production consequences. Comparing this average to something such as the antecedent precipitation index, which is itself a running average of a very inadequately spaced point sample network, or to rain gauge data seems to me to be a severe scale mismatch. It does not strike me as having the kind of leverage either intellectually or in terms of driving natural systems to the point where we can use them authoritatively.

The first recommendation I would come out with is a lot more work on using the present meteorological satellites and finding out the way in which we can use them. They already have one kilometer spatial resolution in the visible region. One kilometer spatial resolution does not put an insuperable burden on society in terms of analysis. That is again another reason for suggesting that we look very, very carefully at the work with the GOES satellites by NOAA personnel, by Merritt, Amarocho and others in the U.S., and by Barrett and others in the United Kingdom.

Unlike rainfall, temperature is both a conservative and continuously distributed variable. There has been a substantial 10-year improvement in U.S. three to six day prediction accuracies. Comparable improvements in rainfall estimation are not in the cards. We need not look to notable improvements in rainfall forecasting accuracy, though some is to be expected as the National Weather Service switches from numerical forecasting with the primitive equation model and a coarse mesh to quantitative forecasts employing the fine mesh and moving fine mesh/quantitative precipitation forecasting procedures.

In a single storm, variations from 8 inches per hour to less than 1/2 inch of rain per hour over a distance as little as one mile may be observed. Knowing these time/space variabilities, we should be conservative about forecasting accuracies. On the other hand, improved observations do at least bring us up to date.

Improved observations on the input side, absolutely must be coupled with modeling. All the evidence to date shows that we are looking only at relatively surficial soil water (0 to 5, perhaps 10 cm.) whatever the wavelength, including microwave. I feel that even passive microwave may not let us go much deeper. With active microwave, we cannot use a much longer wavelength than 30 centimeters in space because of Faraday rotation, so any thought of using very long wavelength imaging radars is out. Remote sensor inputs whether active or passive almost certainly must be coupled with a moisture budget model updated daily. Again, my intuition tells me reliance on remote sensing data alone is not likely. We are already beginning to couple sensing and modeling. I feel confident that that is the wave of the future.

In any case, excessive detail is not warranted nor is wallowing around with oversampling the surface. Soil moisture varies notably in short distances (within-field variability at the surface is very high). Despite this, we find that wheat, for example, can look quite uniform in a soil showing such variability in surface soil moisture. We know that soil moisture spatial variability is less in the deeper horizons. The wheat draws its moisture from tens of centimeters and derives some kind of moisture resource integrated over that depth. I am not too disturbed therefore, about the scatter in surface soil moisture point measurements. Remote sensor data averaged over tens to hundreds of meters are likely to be more meaningful than point measurements. Also I am confident we could use decay functions through time and meteorological satellites with one kilometer spatial resolution in the areas we are mostly concerned with, that is the arid, the semi-arid and the sub-humid lands of the world where the bulk of our small grains are produced.

In summary, I see major research needed on climatic and agro-meteorological water energy-balance modeling in conjunction with a vigorous testing of meteorological satellites and a very critical review of sampling questions.

In regard to other satellites than the meteorological; Landsat D is here in the sense that it has already been at least partially approved by OMB. The work by Kanemasu and a number of others shows that it will have roles in modeling and time-sequential analysis. It is there, we should continue to work on it, and NASA and USDA should continue to fund thoughtful investigations in those areas. Finally, then I am left with active and passive microwave and thermal IR. In my view, there is some, but still largely undefined role for each in a full soil moisture monitoring system. My suspicion is that radar will be very important in the final system. I am very much associated with active radar and I am firmly in that camp. I have recommended before that I think the time is right now to expand aircraft radar R & D so we may move promptly to space experiments with radar. I recommend that we give serious and thoughtful study to the active region for the following reasons: it is the only area that will give us fairly fine spatial resolution along with independence of cloud cover, and it will not be as costly as previous analyses have suggested. We do not have to go with 50 meter spatial resolution. Spatial resolutions of 200, 300, or even 400 meters may very well do the job for most of what we need to do. Costs are in no small measure related to the fineness of the resolution sought.

R.B. MacDonald

In my opinion, a research and development program is justified. I emphasize research on the basis of my experience at Purdue where we initiated a basic research program back in the mid to late 60's to investigate the interaction of electromagnetic energy at various wavelengths with the basic soil material and found that we had to spend considerable resources to collect supportive soil moisture ground truth to adequately describe the moisture of an agricultural field. These studies raised more questions than they answered. There is no question of the importance of the application of soil moisture information, but I think we had better be prepared for a long haul.

What should our priorities be? Very definitely, we need to focus our attentions on one or several of the more important applications. I advocate estimates of the soil moisture over relatively large areas in support of agricultural needs as a priority.

There are some things we can do right now. From Landsat we can observe large areas of severe stress, and with some meteorological inputs we can deduce that the cause is probably a shortage of moisture. We then can use this information for selecting ground stations to get a better estimate of the precipitation and soil moisture for a given affected region.

We need to develop a capability that operates from the ground, from aircraft, and from space, and I am not at all satisfied that we currently have satisfactory techniques from the ground. There is a tremendous need for improved techniques at ground level. Anybody that has worked in this area knows that we have a difficult task of getting enough soil moisture information on the ground to adequately support research.

Basic and applied research should be included in a research program. The applied portion needs to be steered toward operational objectives that are short-term, intermediate-term and long-term. We also must be more thoughtful about defining our requirements, and must recognize that the complexities of these requirements vary. Estimating and measuring soil moisture in the surface of bare soil is probably the simplest requirement. We also have requirements for estimates of soil moisture in the presence of different types of canopies, biomass, leaf area indices, etc.

I think the user community has to do a more conscientious job of establishing its requirements. Evaluation of our present models can be used to determine precisions and accuracies that we could make use of in the immediate future. Extrapolations to estimate the expected improvement in these models would lead us to an intelligent assignment of accuracies required in the intermediate future. Possibly we could extrapolate out to estimates of what we might like to have in 10 years.

With remote sensing we are going to get a direct measurement probably from the surface layer only. We need to intensify our efforts to develop models that relate the moisture in that surface layer to the root zone. I definitely think that researchers have a big job ahead of them in the next year or two to establish a better estimate of the depths to which we can make these measurements and to what precision these accuracies can be expected.

E.T. Engman

My biases are hydrology and water resources. Chris Johannsen indicated that soil moisture data have not really been utilized by users, and I think this is particularly true with hydrology. Our models have soil moisture blocks in them but the use of actual field data even in a research sense has been limited.

I have separated hydrologic and water resource models into two classes for the sake of this discussion. These are operational and planning; and design categories. Operational models could be distributed or lumped parameter models; planning and design models should be distributed. For operational models, temporal scale is more important than the spatial scale. On the other hand for planning and design, spatial scales are more important. Capability of feedback is a feature of the operational models, whereas one time data collection may be all that is necessary for the planning and design models. Data requirements for operational models could be satisfied with satellite measurements; whereas, requirements for planning and design models may be better satisfied with one time aircraft flights.

In answer to Dr. Meredith's questions, a development program is justified, and water resources should be the priority. Both research and operational programs should be emphasized. I know that NASA would like us to precisely define spatial resolution, revisit time, etc., but this is not realistic at the present time. I do not think the user will ever be able to specify the type of requirements that hardware people would like to see. Users should try to adapt modeling or predictive schemes to utilize the information that may be the easiest to get right now.

What type of capability should we develop? Soil moisture estimates at a five square kilometers spatial resolution may be desired, but I do not think we can precisely define this yet.

We should be leaning toward a three day revisit time with seven days as a maximum. As far as spectral requirements are concerned, I think long wave microwave has the most potential for water resources and we should be thinking of evaluating snow and frozen ground in addition to soil moisture.

Finally, what research should we be conducting right now? Well, I think the question of scale is a very important and neglected question in many natural resources applications. In hydrology we use point measurements and yet we do not know how to use these point measurement in a large watershed. We have to learn what sampling schemes are necessary to represent the physical process as we understand it. For example, we do not know how water moves in the soil as certain parts of the watershed are more important than others for generating runoff.

Another question is the use of data. Contouring algorithms of soil moisture or averaging methods must be developed. Use of index areas, particularly if we are talking about an operational model, must be researched. There are certain areas that we could repeatedly measure and, with feedback mechanisms, these index areas may be the best way to solve the problem of forecasting.

T.J. Schmugge

We have indicated that techniques are available that are sensitive to surface soil moisture, but we have not convinced anybody that it could be measured with any high degree of precision with our present knowledge because of the various problems that we have had with ground measurements. Because of uncertainties due to such things as vegetative cover, surface roughness, soil temperature, and soil type, the point has not yet been reached of being able to pin down what the ultimate accuracy is. We have to do continued ground research with tower and aircraft measurements to determine what accuracies can be expected from soil moisture sensors.

In the meantime there is a contribution that a sensor such as the microwave radiometer can make. There is a need for better information on rainfall distribution because the current network of rain gauge stations does not supply adequate data. If we can put up a system that will monitor the soil surface moisture variations on a frequent basis and tie this set of observations to the existing network of rain gauges, we can better estimate the rainfall distribution between stations. Indications are that satellite data can be correlated with antecedent precipitation which hydrologists are currently using. This can be done in the near future with our existing technology. This would not be the ultimate system for measuring soil moisture from space; it would be an interim solution to get us on the road towards making use of observations..

C.J. Johannsen

My views are similar to those of the previous speakers and therefore I will reinforce points which I feel are extremely important. First, a development program on measuring soil moisture from space is justified. I would visualize this as a three-phase simultaneous effort that includes data collection, education and delivery, and research.

Current data collection systems could be used in an intial effort even though the measurements are somewhat crude. The interpretation of those measurements and utilization by the public would be a strong driving force and justification for improvement of the data collection system.

The second phase of an education and delivery system does not presently recieve enough emphasis. We have existing delivery systems within USDA and NOAA. Data should be given to these agencies with established time schedules for getting the information to users. Delivery of soil moisture information needs to be emphasized. Feedback from users would be fairly rapid, especially if efforts were made to solicit their input, and the information should be useful to hardware people for developing and refining instrumentation. The delivery system needs to be making use of existing soils information. We know how much moisture can be held by soils on a regional basis. Currently we can monitor rainfall distribution and estimate evapotranspiration to determine the remaining available soil moisture. A specific measurement of soil moisture from space would greatly improve upon those estimates.

In research, we need to improve the data collection system on the ground as well as from space. I am convinced that we need more rapid procedures for gathering soil moisture information. We need continued research in our modeling efforts. Researchers in the modeling area have convinced me that modeling can very rapidly establish the weakest links in your data and therefore establish the priorities for improving that data. Research should also be conducted on the delivery system with particular emphasis on user requirements. Questions on the types of formats, time requirements, accuracy needs and many other user requirements need to be verified.

Providing experimental data to the user should greatly assist the entire program. This is not one of the times that we should have a 90 to 95 percent accuracy established before we let the public know what we are working on. Providing the user with experimental preliminary information will greatly assist the data collection and research phases. Establishing climatology and meteorology extension position in all states would greatly assist the educational phase.

R.D. Jackson

Today there are many commercial companies that are providing management information to farmers for a price. For example, there is a one man operation in the Pacific Northwest that uses a small aircraft to take 35 mm color IR slides of center pivot irrigation systems. He takes pictures once a week and within 24 hours shows the pictures and consults with farm managers. He points out nozzles that have plugged, areas that need more water or fertilizer, etc. He will only contract with farmers who have at least 5 or 6 center pivots (each one covering about 130 acres). The smaller farmers cannot obtain his services.

What we need is a stationary satellite, tethered between 100,000 and 200,000 feet, that holds several sensors, some of which have not yet been developed. This satellite would be parked over a large agricultural area, and would contain sufficient black boxes so that a farmer, farm manager, or an agricultural consultant could use his own computer, interrogate the satellite and obtain pictures in the visible and IR, and computer produced pictures from thermal IR and microwave.

From this he could rapidly determine when individual fields need irrigation and when they have been irrigated or when rains have occurred. He could get a measure of the growth stage of his crops, and could detect problem fields and nonuniformity in fields. He could verify that automated irrigation systems are properly programmed and function correctly, could verify when the crops are mature, when to terminate irrigations, and could help in predicting yields.

Research in agriculture and in satellite system development is necessary in order for this type of system to come to pass.

D. COMMENTS, QUESTIONS, AND GENERAL DISCUSSION

Comment (E.L. Maxwell)

In respect to what Ray (Jackson) just said, a very similar operation is taking place in Colorado. Individual farmers and corporations having their own aircraft are using 35 mm cameras to study their center pivot operations to identify many of the same problems just alluded to.

There is another item I just became aware of. ASCS in Colorado could not afford large mapping camera operations to study specific problems in small areas. They found a small aircraft owner and for $800 put a small port in the bottom of his aircraft and mounted a 35 mm camera. ASCS is using that system to get updates of agricultural conditions in specific counties in Colorado.

I am going to address some comments to the panel concerning the use of microwave in snow and frozen soil areas, and the temperature independence of radar microwave systems. We should note that radar will not be useful at all under snow and frozen soil conditions because, although the relaxation frequency of water in the liquid and vapor phases is about 40 GHz, when you freeze the water the relaxation frequency drops down into the KHz range. Essentially the rotation of the water molecules becomes so slow that it simply does not try to rotate at microwave frequencies. Therefore, you have dielectric properties for snow and frozen soil that are very equivalent to those for the soil properties themselves, i.e. relative dielectric constants of 2 to 4. Thus, you will not get soil moisture data under frozen soil or snow conditions with radar.

Relative to the temperature independence of microwave systems, we can say they will be relatively temperature independent but not absolutely or completely independent. There will be some errors associated with temperature. It has been noted several times that there is a break point in the dielectric properties of soil as you go through different moisture percentages. The break point is undoubtedly due to chemical binding of the water molecule in the soil particle at low moisture content which affects the ability of the water molecule to rotate readily. Therefore, if you change the temperature of your soil greatly you are bound to have different mobilities of the water molecules. This must cause some variation in dielectric properties and therefore some variation in your calibration system. How great these variations are going to be I cannot say, and I would invite anyone to respond to these comments.

Response (T.J. Schmugge)

Yes, frozen soil would appear to have essentially the same dielectric properties as dry soil. For the idea of snow sensing, the dielectric properties of the ice comprising the snow are similar to dry soils because the water molecules are no longer free to rotate. Therefore its dielectric properties are not the same as they would be in the liquid stage because snow is a much more inhomogeneous media in terms of having a particle lattice and the air spaces in between. The behavior becomes much different and a function of the wavelength. The difference occurs when we get into volume scattering phenomenon which lowers the observed brightness temperature that we observe for dry snow. This is essentially due to scattering of some of the cold sky into the antenna. Thus, we may be able to do something in terms of quantifying snow amounts because of the scattering phenomenon. Another situation that occurs is that when the snow begins to melt, it becomes a very glossy medium and you essentially are observing the black body temperature of the snow.

The dielectric properties do depend on temperature. Hoekstra and Delaney in some of their studies have looked at that temperature dependence. I think it is small but it would have some affect. I think the effect of temperature on the dielectric property is probably one of the smaller errors in our problem.

Response (E.T. Engman)

What I intended regarding frozen soil was not that you measure the soil moisture under the frozen condition, but just give an estimate of whether the soil is frozen or unfrozen. This would be important information for flood forecasting.

Question (H.L. McKim)

What would be the effect of salinity in the soil on the dielectric response?

Response (B.J. Blachard)

Since first attempts to measure dielectric properties of saline soils ran into difficulties due to design of the sample holder, there have been no successful measurements as yet. My greatest concern is whether or not we can separate moisture and salinity effects.

Response (E.L. Maxwell)

There is no reason to expect the salinity of the soil to affect the real part of the dielectric constant because this is essentially due to the presence of the water. We often times make the mistake, however, of assuming that all of the loss factors are associated with the imaginary part of the dielectric constant, the loss of energy due to that rotation. This is not true particularly when you get into saline soils where you have very high conductivities. The conductivity itself is adding to energy losses in the soils associated mostly with polarization. Thus saline soil will affect radar or microwave response but not due to the real part of the dielectric constant.

Comment (E.T. Kanemasu)

With respect to the use of the reflective infrared in modeling yield and crop growth, the temporal resolution required is currently one of the limiting steps. The 9 to 18 day potential coverage with the present Landsat system is not sufficient because of cloud cover to provide estimates of ground cover and biomass required on a continuous and timely basis. What are required are at least 3 Landsats (6 day coverage) or a geosynchronous satellite. Also with respect to agriculture, I think microwave applications are being concentrated at the wrong end of the plant. I think there is more potential for looking at the above-ground portion of the plants than for looking at the first few centimeters of topsoil. I would like to see more emphasis on the assessment of biomass using microwave.

Response (D.S. Simonett)

It depends on the wavelength that you work with, the shorter wavelengths in active microwave never get to the ground where there is significant vegetative cover. If you look at Ulaby's spectrometer results over the range of about 10 GHz to 18 GHz, he found strong indications that observations at six-day intervals give accuracies of crop identification during a 30 day period fully comparable with Landsat, independent of cloud cover. These same wavelengths are also sensitive to contained plant moisture. I am not advocating radar that is preferred to other systems - that is improper. The visible and thermal ranges have their own roles to play. However, short-wavelength radars could usefully supplement Landsat and at least would guarantee delivery of data. Work going back to the mid 1960's shows there is a relationship between biomass, plant moisture and short wavelength (Ka-band) radar return. Ulaby's recent results show relationships between biomass and contained moisture in the plants in the 1 to 2 cm region and the return. Do not discount the possibility of using radar for making estimates of biomass or leaf area index.

Comment (D.G. Moore)

At the present stage of development of applying theory and basic laws of physics to utilizing remote sensors, our knowledge appears to be limited because experiments have been conducted under extremely controlled conditions. The extreme variabilities in nature cause difficulties when testing concepts except for a laboratory or small controlled plot experiments. When attempting to examine the concepts over a wider range of ground variables, many of which are extremely difficult to measure, the interactions of all the main effects create confusion in the data for establishing significance to the real variable to predict. In that sense one may discuss the "art" of remote sensing rather than the "science" at the present stage of development. For advancements of the technology over a broad variety of landscape conditions, both experimental control on site-specific conditions and empirical analysis over the wide variety of conditions and their interactions should be pursued. Until such time that thermal, microwave, or other data to be tested become routinely available for a variety of experiments, advancements in the broad scale evaluations and use will be severely limited.

Response (R.B. MacDonald)

We have to spend considerable effort to develop good experimental designs to come up with data sets that are meaningful to support the kinds of analyses that are required. We should try to acquire and distribute data sets from ground and aircraft environments. I certainly am not against satellite microwave remote sensing. Within the confines of a budget, the data sets from some of these microwave systems at altitude should be made available. However, there are not sufficient funds to do everything. A lot of waste historically occurs because planners put a lot more money into the design of some sensors and platforms than into the utilization of the data in good experimental designs. I submit that there is a host of microwave sensor and satellite plans, and yet I have not seen many good experimental designs for using these data.

Comment (H.L. McKim)

For many of the users the most important information is the management of moisture distribution spatially and with depth as stated today. This information is needed for water resources, waste water management, and hydrological models. In certain instances soil texture and structure can be used to estimate the movement of water through soil where ground measurements of soil moisture cannot be obtained. However, a reasonable scheme that uses soil micromorphology may be able to be developed that would increase the accuracy of using soil physical properties in this manner. Presently there seem to be many problems in using remote sensing methods, especially from satellites to obtain soil moisture data in time and space. The problem may be in the sensor data but may also be related to the acquistion of adequate ground information.

Response (V.V. Salomonson)

I do not know that I am responding to the question raised by Dr. McKim but I want to make an observation. As I have attempted to coordinate and take the lead at Goddard in water resources research, it has been necessary to look into the future and make a decision as to where our research emphasis should be. We have had some pretty good experiences and results from looking at meteorological satellite data in the past for snow cover studies leading to estimates of seasonal runoff. We have studied Landsat data and have had success acquiring observations of land use, surface water area, and snow cover that were useful in water resources management. But it has been my view that we need to develop ways to observe the more fundamental parameters in the hydrologic cycle such as soil moisture, snow water equivalent and wetness, precipitation, and evapotranspiration. For that we need to look at other spectral regions not presently provided by Landsat data.

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From many of the studies it has been my view that there are a lot of things that may be accomplished in water resources by studying the thermal and particularly, the microwave portions of the spectrum.

After deciding where in the broad sense the research emphasis should be, one must consider how to develop and phase intensive studies on the ground, and acquisition of data sets that lead to a fundamental understanding and an appropriate definition of space systems.

I do want to draw on my experience and note that in every case I know of and have participated in there was more information and application derived from space systems than anybody had predicted prior to launch. If we can be permitted to put into orbit systems with microwave sensors and complementary visible and infrared sensors, it is my firm view that we will contribute to our understanding of soil moisture and other parameters in the hydrologic cycle that will be very applicable, and will create benefits that far outweigh the expense and effort involved in developing the systems themselves.

Response (E.T. Engman)

I also would like to respond to the comments of Dr. McKim. I think that we know more about how water moves in the vertical direction than how soil moisture properties vary in the horizontal direction. To me the big unknowns are what is happening horizontally and how adjacent levels of soil moisture affect the hydrology and water movement over the land surface. For applications such as waste water handling and renovations a great deal of detail is required. The only way to get that detail is to make a lot of field measurements, but one is usually talking about something that is a fairly manageable piece of land of perhaps less than 100 acres. Also you take field measurements only once to get the initial properties. Soil moisture variations with time are much more damped at four feet than they are three inches. We must learn how to handle the variation that's occurring at the top of the profile since properties that affect water movement at the top are perhaps much more important than at the deeper depths.

Comment (A.A. Klingebiel)

I would like to address the question regarding vertical water movement through the soil. We can characterize the moisture regime of different kinds of soil. The soil properties certainly are quite different from one kind of soil to another. Of course cultivated or severely grazed soils do tend to seal at the surface. This is related to management of the different kinds of soil. A great deal of information is already known about this in terms of runoff, and amount of water that will actually go into the soil. I see no reason why one cannot for specific areas and for specific kinds of soils arrive at a reasonable estimate of the amount of water that would percolate into and through the soil. The condition of the surface layer does make a difference; it does not matter how permeable the soil might be below the surface if it is sealed at the top. If the water does not infiltrate, it is going to stand on the surface or run off. You can also predict the movement of water down through the soil by knowing the properties of the soil. You can evaluate the kind of soil you have, the land use and the kind of management to arrive at an estimate of the rate of infiltration and runoff.

Question (H.L. McKim)

How do I go into the field and take these measurements? One of the most important aspects that should be considered is the measurement required in the field at the time the sensor is being flown over a site. The number of data points required and the method used to obtain the measurements are extremely important. It is very difficult to say that the differences observed on the data products from the remote sensor are really related to soil moisture without adequate ground truth data.

Response (A.A. Klingebiel)

As you know, there are many factors that influence infiltration and runoff. Soil properties including soil slope, soil depth, soil texture, coarse fragments and soil structure all influence the infiltration and the permeability of the soil. By knowing the kind of soil, these properties can be estimated for areas. By recording experience from small controlled watersheds, one can calibrate the soil moisture regime with different climatic and management conditions. These kinds of data are available from various studies made by the ARS and the SCS. State Soil Scientists of the SCS can help in the development of these figures. You may not get the figures as precise as you would like them, but it seems to me you could come up with some reasonable estimates that would help in making the determinations.

Question (C.L. Wiegand)

Can you give those figures independently of vegetal cover? Does it make any difference on the vegetal cover and if so is there a way to adjust your figures?

Response (A.A. Klingebiel)

Ratings can be given for individual kinds of soil irrespective of the vegetation that occurs on them. The factors are then modified as the vegetation and management are changed. The hydrologic soil factors now used by the SCS in evaluating runoff are examples of the ratings I am referring to. It is my opinion that these general ratings can be improved upon when applied to specific watersheds where more of the parameters are known.

Response (D.S. Simonett)

We have to strike some reasonable balance between the needs for thorough scientific understanding to make us happy and the needs for practical results with simplified systems. If in the microwave region we are unable to get a reasonable working relation between contained soil moisture in the surface few inches and radar backscatter or passive brightness temperature, we had better close up shop. If we have to worry about extremely fine scale water-budget modeling the uncertainties will overwhelm us. For example, there are large areas of the world where we do not know what the soil-water-sealing mechanisms are and the time-rate relationships of them with respect to runoff. Only in the last few years have we learned how hydrophobic some soils are under certain conditions. This applies both to natural plant communities and cultivated soils. Imagine the complexity produced by modeling unknown water relationships on such soils. I am concerned about burying outselves in a mass of detail. I think if we are to get anywhere it has to be with fairly crude systems and with fairly crude relationships, and quite possibly we may not be able to do it quantitatively. We have all talked about doing it as a quantitative measurement. How many quantitative measurements are we taking now from Landsat? What we are doing is using change and logic - in other words deriving empirical relations. I am not arguing against science; but for acknowledgment that operational systems are likely to tend to empiricism and surrogate relations.

Comment (E.C.A. Runge)

In the opening session of the workshop Mr. Carlson talked about the charge he evidently had been given and that was how do we obtain better and more accurate yield models. I suspect that the payoff for many of the things we are talking about is still in this particular area. It seems to me that the political climate is a bit sensitive in this particular area at the present time. I wonder if we have not submerged that in our discussion here today. Yield modeling can be approached from many different angles.

Generally, the action or reaction from the platform has overwhelmed the needs for some of these studies. I do not think we need all kinds of yield models and I think we can prioritize our needs. I buy Dr. Simonett's philosophy that if we have to go down and prove all aspects of plant growth with very detailed measurements we are not going to get very far. I believe there is a big void in our research efforts. We can basically generalize on what we need to know and prioritize our needs.

Comment (R.B. MacDonald)

There are two comments that I would like to add. One concerns the need for development of improved productivity models that relate the surface soil boundary layer moisture to the root zone. We need to spend more dollars on developing these models.

A second point is that we need an improved estimate of precipitation. Better estimates of precipitation using a conventional system together with meteorological satellite measurements, and development of the capability to estimate surface soil moisture directly will give us an improved capability to estimate moisture at depths below the surface. I think more research should be directed toward developing improved ways of estimating precipitation, especially at the more northerly latitudes. I think we are all familiar with the kind of success researchers have had in the tropics, but it does not necessarily extrapolate to higher latitudes where we have different cloud systems.

Response (B.J. Blanchard)

As far as remote measurements of precipitation are concerned, some of you are aware that the Severe Storm Laboratory has been working on this with ARS for about 16 years. Some people whoare very close to this take the approach that it may be another 25 years before we can handle the background problem. What we are using the precipitation for is really to tell us what the soil moisture is.

Another thing I would like to bring out for some of the people who are not doing research in this area and may not be familiar with is that management systems end up working backwards. In July, Seasat will be launched and will carry a radar system, a series of passive microwave frequencies, visible and infrared images, and a scatterometer. Bob MacDonald hit the nail on the head because we have invested all the money in the system and there are no dollars left for the experiments. Beside that, we will have a system in space using those kinds of techniques before we have ground experiments to really build up to that stage. We have some serious problems to address. Are we going to use that satellite data in land experiments to take advantage of it? If we do that and we accomplish the job, then how much effort should go back and be put on truck experiments and aircraft?

Comment (A.D. Nicks)

I am glad to hear that there is a lot more interest in rainfall research than there has been, especially for looking at large areas and the variabilities that can be measured over these. If rainfall and precipitation measurements are important to the remote sensing program, there should be some emphasis placed on doing research in this area or at least getting some research facilities since there are only a limited number of really intensive networks in this country. These are the places where we are going to have data for looking at rainfall variability. Remote sensing data will have to be correlated with some ground measurements.

Depending on what kind of priorities you put on measurement of precipitation you are going to need some other measuring networks throughout the country or throughout the world. These networks are very expensive and there is a lot of data generated from rainfall networks. At Chickasha on 1500 square miles, we have about 60 different soil series across the area. Between even two stations which are about three miles apart, we could have as many as 20 soil series. A "hydrologic model" probably does not exist right now that will accept more than just one rainfall input. I really cannot say that you can simulate the moisture in the top three inches of the soil profile between two stations of the network right now with surface measurements. If you are interested in precipitation inputs to modeling, there should be some decision made on who is going to do the work and what is required.

Bruce Blanchard referred to the severe storms measured by surface measurements and meteorological radar. There has been a lot of work going on in this area since the 1940's. There are varying opinions on radar usefulness but I think most people would say it is very promising. Yet we do not get very good definitions of the storm variability on networks like we have down in Oklahoma from radar.

I think there should be some consideration given to defining precipitation. We can tell you something about the areal variability of it, but we do not know how to use this variability in models.

Comment (F.C. Billingsley)

I would pick up on a different point that Bruce Blanchard made, and that is a question on Seasat synthetic aperature radar. There is another radar that is going to be on one of the shuttle flights. The Seasat radar is intially designed to allow the ocean people to observe wave patterns. For that type of use, certain types of processing are useful. My questions then are; is the type of processing for Seasat adequate or do we need digital correlation? What are the image processing data processing requirements in order to satisfy your research needs; and where should we at NASA be going in terms of trying to develop such a processing program?

Response (B.J. Blanchard)

Land experiments will require digital and repeatable data for quantitative analysis in some experiments, notably soil moisture estimation and watershed runoff coefficient estimates. In my experience with the JPL and ERIM systems, digitized imagery was not repeatable and was not quantitative. Other problems with lack of calibration and angular effects indicated that aircraft SAR should not be used for quantitative studies. These problems can all be eliminated with digital data from a system like Seasat.

Comment (D.S. Simonett)

I understand that we have lost the money for an effort in digital processing of Seasat data, which is unfortunate. However, the work I did in Kansas in 1965 through 1967 was done with imagery that was uncalibrated. Yet, the relative relationships were useable. My reaction is to say at this time in the long run Bruce (Blanchard) is absolutely right. The systems of the future have to be digital and they have to be calibrated, if we seek quantitative answers. However, if somebody would give me the

Seasat optically correlated data and a reasonable amount of money to carry on an analysis I will predict to you that I will come out with some useful empirical results at a single time.

If we wish to have absolute values you cannot get it. So this is the case where I would say the science would demand that we go the more expensive digital route. The practical issues would say that I would be able to live with and at least do something. In fact if we get Seasat data over the central area in California that is exactly what we will do. I must add that Canadian digital processing of Seasat L-band radar imagery over land and sea may well make Canada the prime scientific beneficiary of the radar imaging experiments.

Response (B.J. Blanchard)

I agree with him. On a one-shot basis you can do this. One of the nice features of Seasat is that if you select a group of fields you have the opportunity to look at these same fields on six sequential passes 3 days apart which would give us a lot more strength in developing soil moisture measurements. If you look at it in this regard we need some way to compare this pass with one that is processed 3 days hence.

I would agree there is not much reason to try quantitative analysis of the data that we are getting now and I would further say that if we are going to ever get any real quantitative results from radar information that we have to have more than one frequency. We have to have a dual or three frequency system because there is no way, even with digital analysis that you are going to separate roughness, angle of incidence effect and electrical property effects with just a single frequency. In the future, if we do hope to get some quantitative results we had better put up a system that will operate at more than one frequency.

E. CONCLUDING REMARKS

V.I. Myers

It is appropriate at this point to note several achievements resulting from this soil moisture workshop and to make a couple of observations.

Considerable progress has been made in recent years toward understanding soil moisture phenomenon and in pursuing remote detection feasibility. It is recognized by this group that there is a need for in-depth research, as well as applied research and development activities, in the soil moisture field.

The conclusions reached in the workshop were generally cautious in terms of capabilities but optimistic in terms of the future. Researchers always have to be prepared to take a gambler's risk - it has always been that way.

The greatest promise that may materialize from this workshop would be that the research and development effort will become unified and coordinated. This will surely accelerate the day when we can realize the reality of an operational water resources satellite.

Users are not organized in their requests and requirements for soil moisture information. This can be partly attributed to the realism that soil moisture data by itself is not a final product. It is an input to many other output data products such as watershed runoff, crop yields, irrigation water requirements and many others as brought out in this workshop.

Many individuals or groups express a strong desire for continuous remote sensing soil moisture information. If it could be provided in a relatively simple format there would be little problem with acceptance of the fact of there is need for the data. Agriculture, hydrology and most other resource areas do not have strongly organized groups to voice their remote sensing needs such as is the case with minerals and perhaps shipping interests and others. It remains for a non-political scientific group such as the one meeting here to let these water resource needs be known, hoping that facts and logic can accomplish what an organized voice might otherwise bring about.

The most pessimistic observers surely cannot argue with the concept of bringing together the prepared minds of the best people in the field of soil moisture for the purpose of assessing the present and then planning the future. Optimists of which there are many in the group, would then go further by stating that there is every reason to believe that a concerted effort to develop a useful soil moisture program can produce positive results.

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CHAPTER 7

RECOMMENDATIONS

Significant progress has been made in the development of remote sensing techniques for estimating soil moisture, and some useful applications for soil moisture information have been demonstrated. However, there is an array of questions that must be answered before an operational program is appropriate. A substantial research-oriented program is justified. Following is a summary of recommendations made by participants in the workshop concerning future research and development. These recommendations represent a consensus of opinions from the Workshop participants, but are not necessarily unanimous views.

* Visible, reflective IR, thermal IR, active and passive microwave techniques should be fully considered in a research and development program. At the present time, no single technique appears advantageous over others for the total range of applications. For specific applications one or more of the techniques may be preferred.
* A research program should investigate sampling depth sensitivity, soil moisture profile dynamics, and effects of soil type, surface roughness, and vegetation.
* Use of present meteorological satellites should be more fully explored, particularly for thermal and reflective applications.
* Major attention should be given to assessing moisture profiles using modelling techniques that use meteorological data and can be fine tuned frequently with remote-sensing inputs.

* Research should be oriented around broad resource areas (water resources and hydrology, agriculture, climatology). Examination of resource requirements is more likely to provide insight into sensor and platform design than is a narrower approach of considering a single sensor and its potential.
* Research planning should include scientists familiar with resource problems and sensors. Past planning has appeared to involve hardware design with incomplete knowledge of resource requirements.
* A better balance of funding between building hardware and conducting experiments is required. Too often, insufficient funds remain to adequately conduct the research following development of a sensor system.
* Attention should be given to application of remote sensing for estimating precipitation. For many applications, precipitation is as important as soil moisture.
* The capability for rapid turn around and dissemination of data must be developed. Most users will require soil moisture information within 48 hours of its acquisition. Dissemination should be to the largest logical audience of users in formats of their choosing.
* Provide data to users, upon request, for those limited programs where present capabilities for detecting soil moisture are useful. Examples are desertification, and locust detection.

* Since users are concerned with the interactions of soil moisture with their resource interests, careful consideration should be given to evaluating phenomena related to soil moisture (runoff, infiltration, yield, crop-water stress, etc.)
* Future agriculture/water resource satellites having thermal IR sensors should have a midday equator crossing time. An early morning overpass time reduces significantly the potential of using thermal IR in soil moisture studies.
* Establish better coordination between groups within the remote-sensing community, especially between government, university, and industry.

A soil moisture program should be established to address the recommendations of the Soil Moisture Workshop. The overall objective of this program should be to:

* Implement a research and development program that will lead to the capability of estimating soil moisture from space.

Specific objectives of this program should be to:

* Define physical parameters involved and evaluate the interaction between electromagnetic energy, soil moisture and associated factors.
* Compare and evaluate measurement systems and techniques for measuring and estimating soil moisture.
* Begin consideration of data handling and distribution procedures adaptable to users in water resource management, agriculture, and climate.

* Establish a working group to coordinate the research and development program and obtain user input.

To meet the objectives of the soil moisture program, the following five year (1979-1984) research and development plan is recommended:

* Conduct comprehensive controlled experiments at three to five locations in the U.S. under variable conditions of climate, soils, crops, topography, etc. Suggested locations include arid southwest/west, southern Great Plains, northern Great Plains, midwest, southeast. The research should include:
  - Multispectral (visible, IR, passive and active microwave) sensors
  - Study of sampling depth, vegetation effects, roughness effects, soil moisture profile dynamics, time rate of change effects, resolution requirements
  - Development and improvement of models
  - Test of transferability of models and algorithms between sites
  - Evaluation of phenomena related to soil moisture (precipitation, yield, crop-water stress, plant-water content, etc.).
* Conduct research at ground, aircraft, and spacecraft altitudes
  - Utilize ground and truck-mounted sensors
  - Utilize contract aircraft making repeat visits to the sites
  - Utilize existing and planned NASA and NOAA orbital systems (Landsat C and D, Seasat, GOES, HCMM, Tiros - N, Shuttle, etc.).

* NASA should initiate preliminary planning of a first generation soil moisture/water resources satellite
  - Five to seven years may be required to put the satellite into operation
  - A single satellite oriented toward soil moisture and water resources will lead to more orderly research and development efforts
  - A single satellite will facilitate dissemination of data to users.

OMIT TO END

APPENDIX A

SOIL MOISTURE DEFINITIONS AND TERMINOLOGY

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DEFINITIONS

Water content on oven-dry weight basis

WC_w = weight of water/weight of dry soil

Water content on volume basis

$WC_v = (WC_w)\ (B.D.)$

where B.D. is the bulk density

B.D. = weight of dry soil/volume

Depth of water in soil profile (d)

$WC_d = WC_v \times d$

e.g. $WC_v = .25$; d = 5 cm (2 inches)

$WC_d = .25 \times 5 = 1.25$ cm $\approx$ 0.5 inch water

(daily evaporation rate of a wet soil $\approx$ .5 inches/day)

e.g. $WC_v = .25$; d = 150 cm (5 feet)

$WC_d = .25 \times 150 = 37.5$ cm (14.8 inches)

Soil water potential (ψ_T) is the energy by which water is held by the soil. Because it is based upon a reference level of a free water surface, a wet soil has a low negative number and a dry soil has a large negative number.

$$\psi_T = \frac{RT}{V} \ln e/e_o$$

MEASUREMENT EXAMPLES

Instrument	Measurement
Auger or Probe (Gravimetric Sample)	% water by wt (WC_w)
Neutron Attenuation	% water by vol (WC_v)
Tensiometer	soil-water potential

TERMINOLOGY

Field Capacity (arbitrary concept) - amount of water in the soil profile after a heavy application of water and excess water has drained from the profile (48 hours). The -1/3 atmosphere (bar) moisture content should not be used. Field estimate best after heavy rains or irrigation.

Permanent Wilting Point (PWP) - soil moisture content in the root zone at which the wilted plant no longer recovers turgidity. The -15 atmosphere (bar) moisture content is a reasonable estimate of PWP.

Available Water/Extractable Water Content (AWC) - Difference between the field capacity (FC) and permanent wilting point (PWP). When FC and PWP are on a volumetric basis (WC_v), the difference (FC-PWP) x (Rooting Depth) gives the maximum available water for plant growth or maximum water-holding capacity of the soil. For example, a sandy soil

maximum AWC = (0.06 - 0.025) x 150 cm = 5.3 cm ≃ 2.1 inches

while a silt loam

maximum AWC = (0.36 - 0.15) x 150 cm = 31.5 cm ≃ 12.4 inches

APPENDIX B

SOIL MOISTURE WORKSHOP - ANNOUNCEMENT

SOIL MOISTURE WORKSHOP - ANNOUNCEMENT

A Soil Moisture Workshop is being organized by the Remote Sensing Institute of South Dakota State University. The workshop, sponsored by NASA and USDA, will be held in Room 1400 of the National Agricultural Library at the Beltsville Agricultural Research Center, Beltsville, Maryland, on January 17, 18, and 19, 1978.

The purpose of the workshop is to bring together those who need soil moisture information in their work and those who are developing techniques for the remote sensing of soil moisture. The desired output product is a report which: (1) specifies needs for soil moisture information; (2) describes our current measurement capabilities; and (3) indicates areas where further research is needed. This report will be published as a formal NASA publication.

To accomplish these objectives, small (5-10 member) working groups are being set up in advance of the meeting to prepare position papers that will serve as the basis for the final report of the workshop. The working group on user needs will be split into three subgroups: agriculture, water resources, and weather and climate. Two other working groups will be concerned with remote sensing techniques: (1) thermal infrared and reflected solar radiation approaches and (2) microwave and gamma-ray approaches. These working groups will also make presentations to the workshop. In order to encourage an open discussion at these presentations attendance at the workshop will be limited.

In addition, abstracts of the position papers and a questionnaire will be circulated to all the participants to provoke thoughts concerning soil moisture prior to the workshop.

The agenda is:

1/17 a.m. - Keynote speakers from USDA and NASA. Presentation of summary of agency activities and needs.

1/17 p.m. - Presentation of user working group including statement of modeling capabilities.

1/18 a.m. - Presentation of thermal IR and reflected solar working group.

1/18 p.m. - Presentation of the microwave and gamma working group.

1/19 a.m. - Wrap-up and summary session for the development of final recommendations.

Questions should be referred to: Victor I. Myers
Remote Sensing Institute
South Dakota State University
Brookings, SD 57007 605/688-4184

APPENDIX C

SOIL MOISTURE WORKSHOP

COMMITTEE ASSIGNMENTS

Applications Work Group

Chris Johannsen, Univ. Mo. - Ted Engman, USDA ARS - Co-chairman
Bruce Blanchard, Texas A&M University
Olin Bockes, USDA SCS
Dave Brueck, Babson Brothers
Jim Deardorff, NCAR
Jim Heilman, South Dakota State University
Mel Keener, University of Missouri
Len Myrup, University of California, Davis

Thermal IR and Reflectance Work Group

Ray Jackson, USDA ARS, Chairman
Josef Cihlar, Canada Survey Satellite Office
Jack Estes, Univ. Calif., Santa Barbara
Jim Heilman, South Dakota State University
Ann Kahle, JPL
Ed Kanemasu, Kansas State University
John Millard, NASA/Ames
John Price, NASA/Goddard
Craig Wiegand, USDA ARS

Microwave and Gamma Radiation Work Group

Tom Schmugge, NASA/Goddard - Chairman
Eni Njoku, JPL
Gene Peck, NOAA
Fawaz Ulaby, University of Kansas

Summary Session

Don Moore, South Dakota State University - Chairman
Ted Engman, USDA ARS
Ray Jackson, USDA ARS
Chris Johanssen, Univ. Missouri
Al Klingebiel, USDA SCS Retired
Bob MacDonald, NASA/JSC
Len Myrup, Univ., Calif., Davis
Vince Salomonson, NASA/Goddard
Tom Schmugge, NASA/Goddard
Dave Simonett, Univ. Calif., Santa Barbara

APPENDIX D

SOIL MOISTURE WORKSHOP - AGENDA

SOIL MOISTURE WORKSHOP - Jan. 17-19, 1978
USDA Agricultural Research Center Room 1400 - Beltsville, Maryland

AGENDA

January 17

8:00 a.m.	Registration
9:00 a.m.	Convene - Ruth Whitman, Chairman Announcements, Organization - V. Myers Keynote Addresses - Carl Carlson, USDA ARS Les Meredith, NASA/Goddard
10:15 a.m.	Soil Moisture Definition - Ed Kanemasu, Kansas State University
10:30 a.m.	Coffee
10:45 a.m.	Summary of Organizations, Current Research Efforts and Data Requirements - Jim Heilman, South Dakota State University
12:00	Lunch
1:30 p.m.	Discussion Session on Applications Work Group Co-Chairmen - Chris Johanssen - Univ. of Mo. Ted Engman - USDA ARS
3:00-3:15	Coffee
5:00 p.m.	Adjourn
6:00 p.m.	Social Hour and Dinner at Goddard Employees Recreation Center
7:00 p.m.	Dinner
8:00 p.m.	Illustrated Presentation - "Effect of Changes of Albedo and Ground Moisture on Circulation and Rainfall" - Dr. Jules Charney, Department of Meteorology, Mass. Institute of Tech.

January 18

8:30 a.m.	Discussion Session on Thermal Infrared and Reflectance. Work Group Chairman - Ray Jackson, USDA ARS
10:00-10:15	Coffee
12:00	Lunch
1:30 p.m.	Discussion Session on Microwave and Gamma Radiation Work Group Chairman - Tom Schmugge, NASA/Goddard
3:00-3:15	Coffee
5:00 p.m.	Adjourn

January 19

8:30 a.m.	Summary Session for Development of Final Recommendations. Chairman - Donald Moore, SDSU
10:00-10:15	Coffee
11:45 a.m.	Wrap-up
12:00	Adjourn